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Improving the Process of Designing Cellular Manufacturing Systems

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Abstract

Cellular manufacturing is an important approach to the organisation of production. Large benefits are claimed over traditional functional organisation, and it is compatible with prominent manufacturing theories, such as just-in-time, total quality management, and computer integrated manufacturing. Several very successful applications of cellular manufacturing have been reported, but a wide range of performance improvements has also been observed. Many benefits of cellular manufacturing do not arise directly from changing the organisation and layout of direct production resources, but from changes to the way the production process is operated, managed and controlled, that are made possible by the cellular organisation. Underachievement occurs when companies do not identify and exploit such opportunities. This research aims to address the problem by providing a system wide concept of cellular manufacturing and an improved process to support the design of a cellular manufacturing system based on this concept.

A review of the theory and practice of cellular manufacturing is presented. A model is proposed, which comprises a general set of mutually compatible, production system wide, production system features for supporting or exploiting self-contained groupings of manufacturing resources. A subset of the features from the general model will be appropriate to a particular application of cellular manufacturing. Current processes for designing cellular manufacturing systems do not adequately support the application of such a concept. In particular, tailoring the general concept of cellular manufacturing to a specific situation is identified to be an important but widely neglected design activity. A process is defined that makes concept design explicit, and a matrix-based tool developed to relate the features of cellular manufacturing to a company's performance improvement objectives. The value of this novel approach to designing cellular manufacturing systems is determined to be in facilitating the generation and communication of insight into the nature of cellular manufacturing, encouraging a comprehensive appraisal of the concept and its impact throughout the production system, and focusing limited resources where they will be most effective.

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Finally, many thanks to my Mother and Father for everything they've done for me and for never nagging me about when I was going to get a proper job. Thanks to Ann for putting up with me throughout this research, particularly during the protracted ordeal of writing up. Thanks to the friends and colleagues who have made my time at Cranfield an enjoyable experience.

Author Profile

Tim Nimmons is a researcher within the Manufacturing Operations Research Group at the British Aerospace Cranfield Manufacturing Centre, Cranfield University. Since joining the Centre he has been involved with several industrial projects concerned with planning and implementing cellular manufacturing. He has also lectured and tutored the BAe Fellowship and the Manufacturing Systems Engineering MSc course on this subject.

Prior to joining Cranfield University, the author worked as a quality engineer in a BS 5750 / AQAP design and manufacture environment.

The author has a BSc (Hons) in Material Science from the University of Manchester in 1987 and an MSc in Manufacturing Systems Engineering from Cranfield University in 1991. He is an Associate Member of the Manufacturing Division of the Institute of Electrical Engineers.

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Abbreviations

APICS	American Production and Inventory Control Society
ASI	American Supplier Institute
CNC	Computer Numerical Control
CM	Cellular Manufacturing
DRAMA	Decision Rules for Analysing Manufacturing Activities
DOG	Decision Option Guide
DTI	Department of Trade and Industry
GT	Group Technology
IDEF	ICAM (Integrated Computer Aided Manufacturing)Definition
JIT	Just in Time
LE&S	Lucas Engineering & Systems
MRP	Manufacturing Resource Planning
MSE	Manufacturing Systems Engineering
OPT	Optimised Production Technology
PFA	Production Flow Analysis
PPC	Production Planning and Control
QFD	Quality Function Deployment
SBAC	Society of British Aerospace Companies
SMED	Single Minute Exchange of Dies
TQM	Total Quality Management
TPM	Total Productive Maintenance
WCM	World Class Manufacturing
WIP	Work in Progress

Chapter 1 Introduction

The subject of this thesis is the design of cellular manufacturing systems, and the development of a practical method that will improve the design process. The work was undertaken with close industrial collaboration to maximise insight into the practical problem of cellular manufacturing system design and to support the development of a useful solution. Chapter 1 provides some background to the research domain, and defines the research problem and aims. Finally the structure of the thesis is explained.

1.1 Competitive Environment

Since the mid-1960s manufacturing capacity has been catching up with demand in most industries, creating a keen competitive environment (Hill 1985). Moreover, increasing rates of technical innovation and the growth of the global economy have provided greater consumer choice and created fragmented markets populated by sophisticated and demanding customers. Hammer and Champy (1993) note that since the 1980s the dominant force in the supplier-customer relationship has shifted towards the customer. "In place of expanding mass markets, . . . companies now have customers . . . who know what they want, what they want to pay for it, and how to get it on the terms they demand." (p. 21). Hanson (1992) asserts that, "World-class manufacturers will be recognized by the leadership they provide in attacking and resolving complex customer problems." (p. 164).

Shingo (1989) points out that in a competitive environment a product's price will not be the sum of production costs and the company's desired profit margin. Rather, the market will set the price and profit will be determined by the cost of production. That is: *Profit = Price - Cost*. Under these circumstances profit can only be improved by removing waste from the production system. Thus, companies have come under increasing pressure to cut costs.

Furthermore, the nature of competition is also changing. Products no longer only compete on price alone. Consumers are increasingly considering the total life cycle cost of a manufactured product and emphasising the relative importance of non-price factors, such as quality, innovative design, and delivery performance in their assessments of value-for-money (Finniston 1980; Tidd 1994).

The Japanese first set new standards of performance in quality. For example, in a trial undertaken by Hewlett-Packard in 1980, the inspection failure rate of memory chips was at least twenty times greater for American than Japanese suppliers (Hayes, Wheelwright and Clark 1988). However, excellent quality is now becoming a condition of entry to many markets. DeMeyer et al. (1989), based on data from their 'Manufacturing Futures' surveys, suggest that Japanese manufacturers have sufficient advantage in quality dependability and cost-efficiency to focus on speed and flexibility as sources of competitive advantage. The ability to produce a broad range of products allows the coverage of more market segments, and Hill (1985) notes that, a company with quick lead times will be able to meet delivery date requirements when only some or even none of the competition can do so. Stalk (1988) describes this as time based competition. Cost benefits can be obtained from reducing the time to transform resources into finished products, while fast response, and the ability to constantly upgrade the technical sophistication of products through rapid introduction of new products, attracts the most profitable customers.

Clark and Fujimoto (1991) note that the market conditions described above have combined to push new product development to the centre of the playing field in the competitive game. Hammer and Champy (1993) explain that, "not only have product and service life cycles diminished, but so has the time available to develop new products and introduce them." (p. 23).

Developing competitive advantage has become a moving target, and the growing intensity of competition is speeding up the pace of change. Peters (1989) writes, that "For the foreseeable future there is no such thing as a 'solid' or even substantial lead over ones competitors. Too much is changing to be complacent." (p. 3). Uncertainty in the form of fluctuating currency prices, changing political boundaries and trading policies, and the rate of new competitors emerging, has increased with the size of the market place. Technology is also constantly altering both, the nature of products, and the nature of business and production. Peters' view is that change is becoming continuous, and that only those companies who can proactively create new competitive opportunities in such an environment will be successful.

The DTI report, Manufacturing into the Late 1990s (PA Consulting 1993) reviews external business drivers under the following headings: the global economy; demography and lifestyles; the environment; markets, products and services; competitors; technology; and suppliers. Their effect on the challenge facing manufacturing companies is summarised below:

- *Customer expectations* and power will continue to grow, and exert pressure on manufacturers to provide more comprehensive product packages, increase product choice, enhance product performance, improve quality, delivery and service, and charge a competitive price.

- *Complexity* will increase as product and processes contain more technologies and companies are required to supply wider product ranges of more customised products to more customers and market niches.

- There will be more *Uncertainty* as product life cycles diminish and fast moving niche competitors fragment markets, continually increasing the performance required to be competitive. A wider range of customers, more product variety more customisation, and shorter delivery lead times will all reduce demand stability.

- Companies will have to contend with increasing *competitive and legislative pressures*.

This is corroborated by Computervision's survey of manufacturing attitudes (1994). Of the manufacturing sites that responded, 91% expected some increase in the level of competition over the following five years. Over half of the respondents expected much more competition in that period compared with just over a third who felt the same way in the previous year's survey.

1.2 Cellular Manufacturing: An Appropriate Strategy

Cellular manufacturing is an approach to the organisation of production that exploits product focused, semi-autonomous groupings of production resources to achieve high levels of competitive performance. In other words, teams of people are formed and provided with all the equipment necessary to be able to complete the manufacture of a defined range of products through a major processing stage. This form of organisation has several beneficial characteristics that can be exploited (for example, by enabling set up and batch size reductions) to improve lead times, quality, delivery reliability, and costs. It is also claimed to provide more humane working conditions, generating high levels of job satisfaction and a motivated workforce, which, in addition to any moral argument, may also give rise to increased performance (Black 1983; Burbidge 1961, 1979, 1989; Fazakerley 1976; Gunasekaran et al 1994; Jackson 1978; Mechanical Engineering EDC 1975; Schonberger 1983). These characteristics have been identified to be particularly suited to tackling the combined challenges of increasing performance requirements, competition, uncertainty and complexity highlighted in section 1.1.

Skinner (1974) and New (1992) assert that a focused manufacturing task is essential to achieving truly competitive performance, and the simplification of material flows is a significant enabler of Just-in-Time (Cheng and Podolsky 1993; Harrison 1992; Schonberger 1982, 1983). Swamidass and Newall (1987) identify manufacturing flexibility as an appropriate strategy for dealing with uncertainty in the environment. Drucker (1990) describes how cellular manufacturing provides a mechanism for managing complexity by decomposing the production system into a *'flotilla'* of product focused modules. The modular structure of cellular manufacturing provides focus within individual cells, allowing each to concentrate on achieving high levels of performance to satisfy their particular customers' requirements. Each cell within the flotilla however, is independently manoeuvrable, making the factory as a whole tremendously flexible.

Herbst (1976) suggests that autonomous teams are effective in unstable conditions due to their capacity for learning, and their ability to adopt novel and temporary internal structures. Hayes, Wheelwright and Clark (1988), Schonberger (1986), and Drucker (1990) stress the importance of complexity reduction, alignment of information with accountability, and workforce empowerment in enabling both, high performance, and continuous learning and improvement. These characteristics can be seen in the architecture of clear, direct, material and information flows, and the self managing teams upon which cellular manufacturing is based.

A detailed description of the salient features of cellular manufacturing are presented in Chapter 2. While the cell concept has been developed from work in both batch and flow environments, Alford (1994) reports that the majority of its application has been in batch production. This is not surprising as batch production accounts for 75-85% of the output from western manufacturing industry (O'Grady 1988), and the benefits of cellular manufacturing appear to be more tangible to this environment. Consequently, the focus of this research is the application of cellular manufacturing in batch production environments. The aerospace industry provides many typical examples of batch manufacture.

1.3 The Aerospace Industry and Cellular Manufacturing

In line with the general competitive situation, over capacity in the civil aerospace industry is increasing levels of competition. Ingersoll Engineers survey (1994[b]) reported that the civil aerospace industry has become a mature global industry subject to the full competitive pressures of cost and delivery. An increased demand for product variety is also expected.

The demise of the Cold War has also led to reduced sales and therefore similar increases in competition in the military aircraft industry.

Recently significant emphasis has been placed upon the reduction of lead times within the aerospace manufacturing industry. For example: Airbus Industries (Omand 1994) has set aggressive lead time reduction targets which in turn require that BAe Airbus reduce wing delivery lead times from seventeen to four months; Rolls Royce claimed to have achieved significant lead time reductions through the use of cellular manufacturing and are now pursuing similar performance improvements from their suppliers (Williams and Keeting 1995); the aerospace programme of the Innovative Manufacturing Initiative (EPSRC 1996) has an objective of reducing industry lead times, and the SBAC Competitiveness challenge (DTI 1995) advocates the use of cellular manufacturing to reduce lead times.

Ingersoll Engineers identify cellular manufacturing as one of the foundations upon which the necessary capabilities can be developed within the aerospace manufacturing industry. There is also significant empirical evidence to suggest that cellular manufacturing can be successfully applied to this environment (Cook 1994; Kellock 1992; Macilwain 1991; Masom 1993; Omand 1992; Williams and Keeting 1995)

1.4 Extent of Cellular Manufacturing Application

From the mid-eighties onwards there has been a considerable increase in the acceptance and implementation of cellular manufacturing. The surveys of cellular manufacturing in 300 UK engineering companies, undertaken by Ingersoll Engineers (1990, 1994[a]), reported 73% of companies using cellular manufacturing with over a quarter of those being fully cellular. Penetration was found to have increased by 40% between the two surveys. Significantly, only one company had tried cellular manufacturing and then abandoned the approach.

While the development of the cellular manufacturing concept has generally taken place in the engineering industry, there is evidence that its benefits are being more widely recognised.

For example, Mugwindiri, Groves and Kay (1995) report a recent increase in the use of cellular manufacturing in the furniture industry.

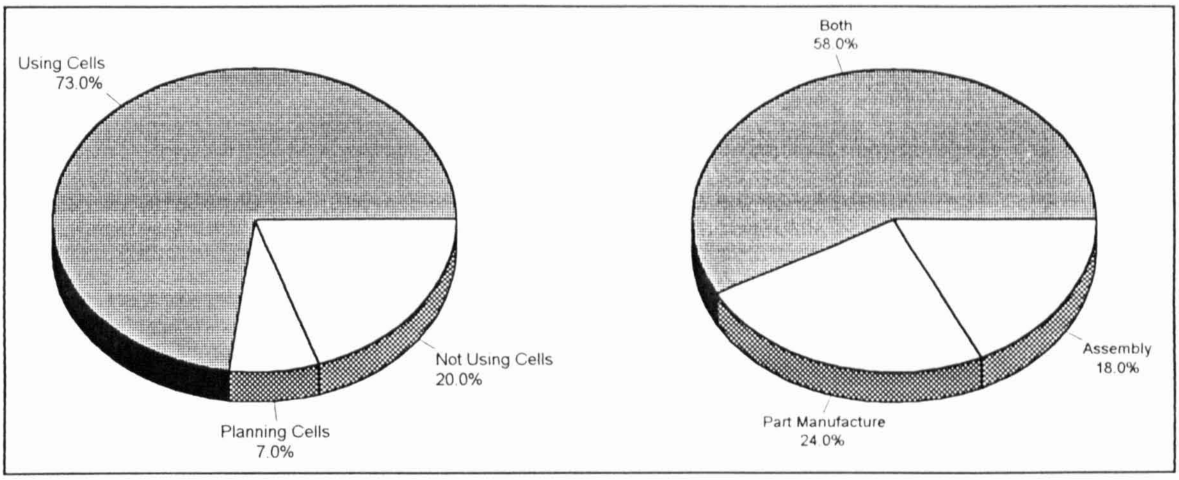


Figure 1.1 Penetration of Cellular Manufacturing (Source: Ingersoll Engineers 1994)

1.5 Performance of Cellular Manufacturing Implementations

There are many prominent success stories concerning the implementation of cellular manufacturing, such as Northern Telecom (Taheri 1990), Beavers (Booth 1988), Deere and Co. (Welke and Overbeeke 1988), Cummins (Venkatesan 1990) and Champion Irrigation Products (Kumar and Hadjinicola 1993). It is also associated with the triumph of Japanese manufacturing (Harrison 1992; Schonberger 1982, 1986). Several surveys of cellular manufacturing implementations have also been conducted (Dale and Wiley 1980; Wemmerlöv and Hyer 1989; Ingersoll Engineers 1990). Although these reports tend to emphasise the positive aspects of their findings, a significant proportion of companies appear to obtain relatively small performance improvements.

Figures 1.2 and 1.3 show the results of Wemmerlöv and Hyer's survey, and the Ingersoll Engineers survey respectively. While spectacular results are still in evidence, it is clear that they are not an inevitable consequence of implementing cells. The difference between the best and the worst improvements is very large.

Benefit	Average Improvement	Range
Reduction in Throughput Time	45.6%	5% to 90%
Reduction in WIP	41.4%	8% to 80%
Reduction in Materials Handling	39.3%	10% to 83%
Improvement of Operator Satisfaction	34.4%	15% to 50%
Reduction in Number of Fixtures Required	33.1%	10% to 85%
Reduction in Setup Time	32.0%	2% to 95%
Reduction in Space Needs	31.0%	1% to 85%
Improvement in Part Quality	29.6%	5% to 90%
Reduction in Finished Goods Inventory	29.2%	10% to 75%
Reduction in Labour Cost	26.2%	5% to 75%

Figure 1.2 Benefits of Cellular Manufacturing (Source: Wemmerlöv and Hyer 1989)

The distribution of performance within this range is not shown but a clue can be found in Ingersoll's data on lead time and work-in-progress. Figure 1.13 indicates that nearly half of the companies using cellular manufacturing will have got less than 25% improvements in two of the key areas of performance improvement associated with cellular manufacturing.

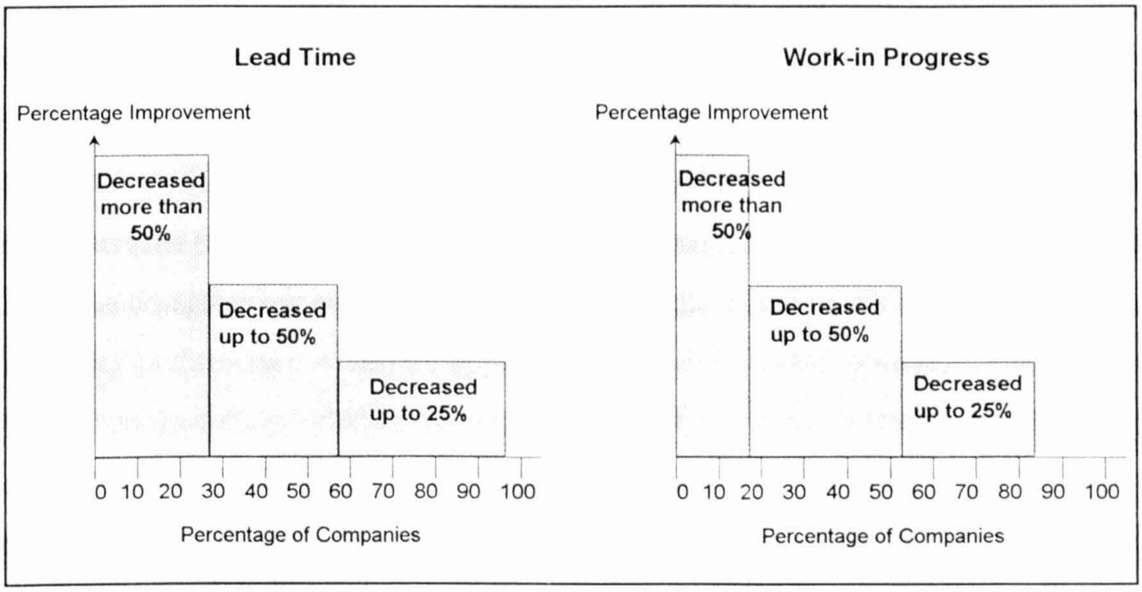


Figure 1.3 Distribution of Performance Improvement (Source: Ingersoll 1990)

1.6 Research Problem

Cellular manufacturing has been shown to be an important concept for organising production in the current competitive environment. Many companies are experimenting with using cellular manufacturing, however, there is a significant range in the performance improvements achieved from introducing cellular manufacturing, with some companies obtaining relatively little benefits (Wemmerlöv and Hyer 1989; Ingersoll Engineers 1990). Most commentators choose not to interpret the survey results in this way, and emphasise instead, the demonstrated potential for large improvements.

Burbidge (1979) suggests that the benefits of cellular manufacturing will not be obtained, simply by grouping men and machines to produce a family of products. Rather, this new structure provides opportunities to radically change the way production is managed. It is the exploitation of these opportunities that significantly improves performance. Harrison (1992) argues that the limited scope of many early cellular manufacturing implementations led to their underachievement and eventual disuse. The three examples he gives are: isolated experiments with cellular manufacturing that although successful play no part in overall company policy; limiting the application to the physical rearrangement of facilities; and conflict arising from neglecting to change payment and performance measures to reflect the requirements of the new system. Kirton and Brooks (1994) report that a superficial conception of cellular manufacturing commonly leads to cells not meeting their performance expectations. Such cells are described as "white line cells", in reference to the extreme cases, where the change may comprise little more than painting lines round existing machine groups and changing their names to include the word cell. These issues are often associated with under performance in current applications of cellular manufacturing. The opinions expressed above are supported by the findings of Ingersoll Engineers (1990), which suggest that the scale of performance improvements is related to the proportional investment in people, and management and control systems, over machines and buildings.

Despite the body of evidence to suggest the need for a more holistic treatment of cellular manufacturing, there is little evidence of this in the literature. Many definitions and descriptions of cellular manufacturing emphasize its structural comparisons with traditional production systems, and neglect the wider issues that have been identified as being essential to its success. Sule's (1988) definition of Cellular manufacturing, as a system in which a large number of common parts are grouped together and produced in a cell consisting of all the machines that are needed to produce that group, is typical. Similarly limited definitions are expressed by Flynn and Jacobs (1987), Fry, Wilson and Breen (1987), Huang and Houk (1985) and Shafer and Rogers (1991).

The majority of research into the design of cellular manufacturing systems focuses on discrete elements of the manufacturing system, for example, cell scheduling, job design and in particular part machine grouping (Wemmerlöv and Hyer 1986; Offodile, Mehrez and Grzar 1994). Little work has been done on the development of procedures to integrate these design decisions. Lewis and Love (1993) argue that although cell formation has received a significant amount of attention, this is of a narrow nature, stopping well short of what is necessary to design a cellular manufacturing system. Their findings suggests that little has changed since Black (1983) wrote, "Few rules and virtually no theory exist for designing cellular manufacturing systems." (p. 38).

The research problem can therefore be stated as follows:

How to provide a system wide concept of cellular manufacturing, and support the design of a cellular manufacturing system based upon this concept.

1.7 Research Aims

Based on the research problem stated above, the aims of this research is defined as follows:

i. Develop a system wide definition of cellular manufacturing that provides a useful reference to guide the design of cellular manufacturing systems.

ii. Identify the strengths and weaknesses of current approaches to the design of cellular manufacturing systems.

iii. Determine the requirements for an improved approach to the design of cellular manufacturing systems.

iv. Develop a practical method for designing cellular manufacturing systems that satisfies the requirements defined by 3 above.

v. Test and refine the method through practical application in an industrial case.

1.8 Research Strategy

The research strategy adopted was largely influenced by the applied nature of research. According to Robson (1993), "One of the challenges about carrying out investigations in the 'real world' is in seeking to say something sensible about a complex, relatively poorly controlled and generally 'messy' situation." (p. 3). Rather than, just gaining knowledge, finding causes, determining the relationship between variables, and developing and testing theories, he suggests that "real world research" emphasises solving problems, prediction of effects, looking for robust results (getting large effects) and identifying actionable factors. Meredith, Raturi, Aoako-Gyampah and Kaplan (1989), in their paper arguing for a broader approach to research methodology in the arena of operations management, assert, that, "Operations is an applied field and its research should be usable, in some fashion, in practice." (p. 300). A survey of UK managers undertaken by Bennett and Gill (1978) revealed the opinion that research was initiated by academics who are often insufficiently familiar with the managerial culture, and addressed irrelevant problems. It therefore lacked credibility and was considered to be of little practical value. To ensure that this research was both relevant and realistic, both the problem definition and the solution development were undertaken in close contact with industry.

The research strategy adopted was based on exploiting the close industrial relationships enabled through the British Aerospace Cranfield Manufacturing Centre. This provided opportunities to obtain information about the practical aspects of designing cellular manufacturing systems, both, through interviews with practitioners, and by actively participating in projects concerned with design of cellular manufacturing. Continued contact with the sites involved over the duration of the research has provided a valuable longitudinal dimension. The relationship between BAe and Kawasaki Heavy Industries also enabled the author to visit Japan to observe the Kawasaki Production System first hand in its native environment.

In addition to manufacturing practitioners, consultants at Ingersoll Engineers, Lucas Aerospace, Human Centred Systems, Price Waterhouse were questioned about their experience of designing cellular manufacturing systems. The author has also communicated directly with academics who have significant research and practical interests in cellular manufacturing and manufacturing systems design, such as Professor J. Burbidge, Professor U. Wemmerlöv, Professor K. Hitomi, Dr P. Forrester and Dr B. Wu.

The practical work was supported by a thorough review of the literature in the research domain. CD-ROM facilities at the Cranfield University library were used to interrogate the following databases: Recent Advances in Manufacturing (RAM), Compendex Plus, INSPEC, National Technical Information Service (NTIS), ABI Inform, and the DIALOG Information Services Aerospace database. Searches in the main subject area of cellular manufacturing and group technology were supplemented by searches in manufacturing/production systems design, manufacturing strategy, systems methodology, just-in-time, lean manufacturing, and quality function deployment.

Test Strategy

Cellular manufacturing is a complex concept, having an impact upon many components of a manufacturing system, and the success of a cellular manufacturing implementation can be influenced by both its design and the way it is implemented. Moreover, the design of the system and the implementation will be influenced by many factors such as, the performance objectives, and the nature of the existing system. Human factors, such as the skills and experience of those involved, the management of the decision process, and the industrial relations environment play a significant role in the process of planning and implementing cellular manufacturing. Therefore, a case study approach was identified as being appropriate to the nature of the research problem being tackled.

Yin (1989) identifies the case study as having a distinct advantage when a how or why question is being asked about a contemporary set of events, over which the researcher has little or no control. Yin also suggests that case study research is appropriate for attributing causal relationships as well as exploring or describing a situation. A major strength of the case study is the ability to consider multiple variables, possibly collected from different sources, using a variety of data collection techniques. It is therefore particularly suited to investigations which need to study both, a particular phenomenon, and the context within which the phenomenon is occurring. It is apparent from the advantages of the case study method described above that it is an appropriate approach for understanding the design of cellular manufacturing systems when studying both, historical and contemporary design events.

Data collection methods were selected for their ability to obtain the contextual information necessary to provide a substantial understanding of the practical problems, and their potential for taking advantage of serendipitous findings about what factors affect the success of a cellular manufacturing implementation. These included semi-structured and free form interviews, participant observation and action research.

The new method for designing cellular manufacturing systems developed by this research was applied in an industrial case by a team of academics and consultants from Cranfield University and Cranfield Innovative Manufacturing, including the author. A review of the design process was undertaken involving self reflection by the author and a series of interviews with key participants. Figure 1.4 illustrates the three prime requirements for a valid test of the method. Unfortunately it is impossible to achieve all three in a single test.

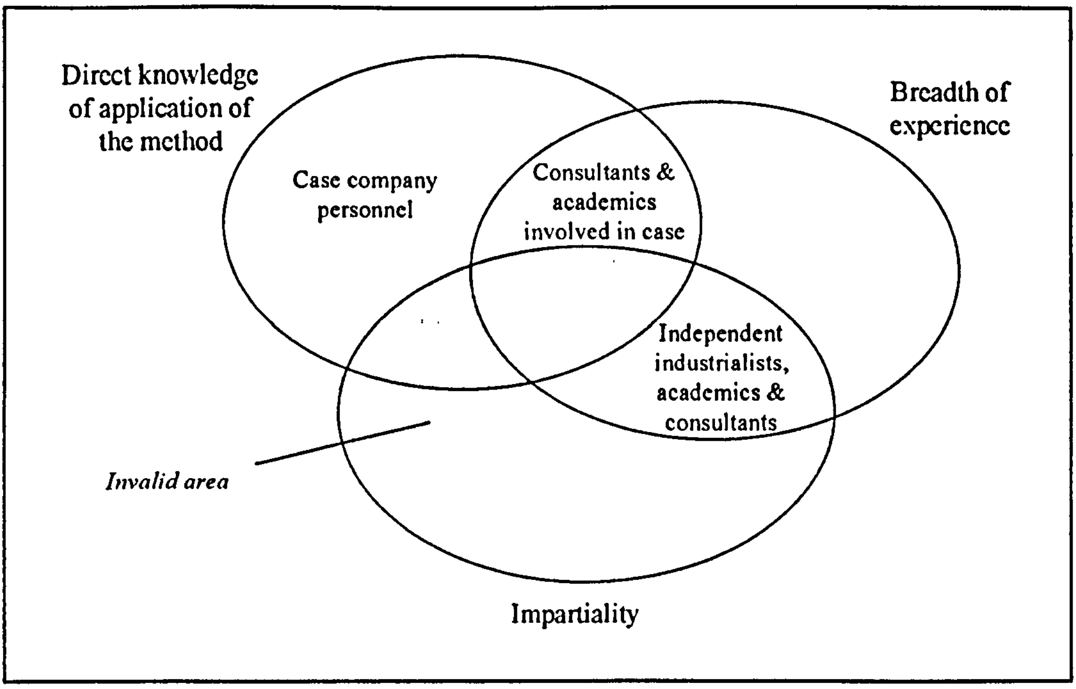


Figure 1.4 Test Strategy: Target Populations for Data Collection

While it was felt that the experience of the consultants and academics involved in the case equipped them to assess the extent to which the findings of the test were generally applicable, it was also thought that their close involvement with the method and the case may affect their interpretation of the results. In order to increase confidence in the external validity of the research, the results from the case were triangulated by asking independent industrialists and consultants to appraise the method.

1.9 Industrial Context for Research

This research was sponsored by the British Aerospace Cranfield Manufacturing Centre. This centre was set up by British Aerospace and Cranfield University in 1990 to provide medium term research, training and consultancy to BAe's aerospace manufacturing operations.

BAe were aware of the potential advantages of cellular manufacturing and were experimenting with its application from 1989 (Williams 1991). This provided the impetus and role model for introducing cellular manufacturing throughout BAe's manufacturing facilities. To support this, a programme of research was set up in 1991 to look into the issues surrounding the planning and implementation of cellular manufacturing. The BAe Cranfield Manufacturing Centre provided the researcher with access to BAe sites to gather information, both as an observer and as a participant in cellular manufacturing projects. The experience obtained with BAe has enabled the author to get involved with designing cellular manufacturing systems for other companies. One of these companies provided the industrial case study for the research.

1.10 Thesis Structure

The key points addressed in each chapter of the thesis are summarised below.

Chapter one provides the context for the research. The research problem, research aims are defined and the research strategy and thesis structure are presented.

Chapter two reviews the theory and practice of cellular manufacturing. A novel model of cellular manufacturing is defined, and substantiated by the compilation of a wide range of cellular manufacturing system features and their desired effects from the review of theory and practice. The implications of this model for the task of designing cellular manufacturing systems are discussed.

Chapter three reviews the theory and practice of designing cellular manufacturing systems. The strengths and weaknesses of current methods are discussed.

Chapter four brings together the conclusions of Chapter 2 and Chapter 3 to specify and develop an new improved approach to designing cellular manufacturing systems that builds on the general model of cellular manufacturing features and effects described in chapter two. The importance of the concept design stage is highlighted, and a process for concept design is specified.

Chapter five presents a new method to support the concept design stage of the cellular manufacturing system design process. The method uses matrices to provide a structure for a company to explore the relationship between their current system, their performance improvement objectives, and the features of cellular manufacturing.

Chapter six presents a validation of the approach to designing cellular manufacturing systems. The method is tested in an industrial case and against the experience of industrialist, academics and consultants. Support is sought for the flexible general model of cellular manufacturing, for the overall process for designing cellular manufacturing systems, and for the matrix based concept design procedure.

Chapter seven discusses and concludes the findings of the research in comparison to the problem defined and the research aims submitted by this thesis. The research process and and the limitations of the findings are discussed and further opportunities for research arising from this work are identified.

Chapter 2 The Nature of Cellular Manufacturing

Chapter 2 reviews current theory and practice of cellular manufacturing with the objective of reaching a definition that can be used as a basis for studying and improving the design process. The historical development of cellular manufacturing is presented in order to identify the basis upon which this manufacturing system was developed and also to clarify the alternative terminology used. The relationship between process position, layout and work organisation, is used to compare cellular manufacturing with traditional manufacturing systems. The insight from these analyses is then used in conjunction with a more general review of cellular manufacturing theory to construct a features and effects model for the general case of cellular manufacturing.

In order to study the process of designing cellular manufacturing systems, it is necessary to have a clear understanding of the cellular manufacturing concept. Cellular manufacturing appears to be the result of several research disciplines, applied to different manufacturing environments, coming together, and their subsequent evolution. This has led to a confusion of terms and theories for describing similar manufacturing systems and explaining their performance. This chapter will therefore begin by reviewing the origins of cellular manufacturing to provide an adequate foundation from which to develop a useful definition.

2.1 Historical Development of Cellular Manufacturing

Cellular manufacturing developed from the convergence of two broad themes of research. On one hand there was an endeavour to achieve the economies of mass production flow lines for a batch production environment. On the other hand, mass production methods were not standing still. Efforts were being made to optimise the organisation of flow lines in order to improve flexibility, minimise balancing losses, make them more robust and improve the quality of working life. Fortunately, the compromises to flow line principles required to make their application to batch environments practical, reflected the new direction in work organisation for mass production. A few seminal contributions to the literature are described below.

2.1.1 Batch Production

While there are some early examples of product organisation in batch production environments, it took some time before this approach to manufacturing organisation was formalised, and widely acknowledged. Flanders (1924) clearly articulates many of the problems resulting from batch production and the solutions he describes would today be referred to as cellular manufacturing. Figure 2.1 provides a brief indication of Flanders' production philosophy.

Flanders (1924) recognised that work organisation based upon groups of similar machines was disadvantaged by "the constant movement of work from department to department with its consequent slowing up of the work flow, division of responsibility and difficulty of control." (p. 698). The alternative he suggested, was to arrange facilities by product such that any individual piece stays in a single department until it is completely finished. He explained that, "All long waits ... are eliminated, and with them the expensive items of storage space and idle capital for inactive stock. The ideal aimed at has been that of a small, fast flowing stream of work instead of a large, sluggish one." (p.706). Flanders also described simplifications to production control, inventory control, and cost accounting procedures that were made possible by changing to product organisation. These enabled overhead costs to be controlled despite a dramatic down turn in demand.

Figure 2.1 An Early Example of Cellular Manufacturing.

Mitrofanov's (1966) "Group Technology" is frequently quoted as a major inspiration for the development of cellular manufacturing. His work on the relationship between component shape and processing methods through the 1940s showed how parts requiring similar set-ups on a single machine, could be grouped and processed together, to minimise the time wasted while changing the machine set-up.

Burbidge (1958, 1961) was one of the first to recognise the wider possibilities of such findings, and draw them together into a comprehensive production system. Presenting a case against the economic batch quantity theorem, he argued that maximum profit is obtained by producing parts in balanced assembly sets, at a rate that provides the maximum turnover of stock. He advised that flow-line production and period batch control would achieve this, and claimed that they were practicable in a low volume-high variety situation, if components were grouped into families such that, ". . . all the components in each family are made by similar operations, in the same sequence, on the same plant." (Burbidge 1961, 783). Burbidge (1961) cites Alsthom-Lecourbe as a practical example of such a system. Results reported were, big reductions in stock, three to four times the output from the same floor area, a reduction in lead time for new orders from three months to three weeks and a 45% reduction in throughput time per order, reduced tooling costs and improved operator morale. Sidders (1962) also presented a case where several machines were grouped such that they could produce an entire family of components from start to finish. Importantly, he identified that the beneficial effects of cellular manufacturing are not confined to the production process. Simplification and cost reductions were reported in indirect activities such as production control, stores management, cost accounting and production planning.

By 1963 Burbidge confidently wrote, "There are already a number of successful applications of line production to diversified product manufacture; the main difficulty now is not to justify the change, but to decide how to put it into practice." (p. 742). He went on to develop his Production Flow Analysis approach to planning the grouping of parts and machines. The creation of new approaches to this particular problem has since dominated research in cellular manufacturing, and is discussed more fully in Chapter 3. Despite some success, interest in cellular manufacturing was not sustained, and did not really take off again until the mid 1980s (Ingersoll Engineers 1990).

A similar revolution in the organisation of production had taken place at Toyota in Japan. Environmental factors emphasised the deficiencies of batch production and led to development of a product focused organisation to enable control of work-in-progress (WIP) between processes. The origins of the Toyota (Just-in-Time) Production System are summarised in the text box below. While this approach was also not widely adopted initially, its success eventually led to extensive emulation. The effective use of product organisation in batch production environments by the Japanese alerted western industry to the missed opportunities of their own experiments with cellular manufacturing.

Toyota's particular problem in the late 1940s was to achieve a tenfold increase in labour productivity to catch up with US car manufacturers, while only producing small numbers of many types of car for their domestic market (Ohno 1988). At that time, Japan was in the grip of a recession brought on by US imposed credit restrictions aimed at stamping out post war inflation. Toyota were forced to shed 25% of its work force. They resolved the ensuing dispute by guaranteeing the remainder life time employment and seniority based pay in return for flexible working agreements and cooperation with improving the production process. This had the effect of making labour a fixed cost, that over the long term was more significant than machinery costs, which could be depreciated and scrapped (Womack, Jones and Roos 1990). Ohno's solution in the engine machining shop was to develop a system with minimum inventory. They rearranged machines from their functional arrangement into process sequenced "cells", and a pull system was developed such that a process only produced output when the following process was ready for it. As there was not sufficient demand to keep all the machines running all of the time, machines were adapted (autonomation) so that each operator managed more than one at a time.

Figure 2.2 Development of Cellular Manufacturing at Toyota

2.1.2 High Volume, Flow Production

This thesis is primarily concerned with the application of cellular manufacturing in batch production environments. However, as flow production was the ideal being pursued by batch manufacturers, it is instructive to consider the parallel developments that took place in the organisation of flow production. Rising competition and market demands for increased product variety and shorter product lives, had made apparent, previously unimportant structural deficiencies of flow line, such as inflexibility, line balancing inefficiencies, and lack of clear accountability for product quality. The nature of work on the production line, combined with increased levels of education among the workforce and a changing social climate also led to consideration of the relationship between job design and productivity. Boredom, monotony, and alienation of production line work are considered by many to be at least partially responsible for industrial disputes, increased absence and labour turnover and reduced quality and productivity (Kelly 1982; Wild 1975).

Job design has its basis in the assumption that the nature of work will affect workers' morale and motivation to perform. Hence, the needs of both an enterprise and its individual workers can be supported simultaneously, by manipulating the significant dimensions of the job design. According to Buchanan (1979), job design theories and techniques have developed from the simple elimination of monotony and boredom through job rotation and job enlargement to job enrichment theories that incorporate explicit theories of motivation (eg. Herzberg's (1966) two factor theory of motivation and expectancy theory which accounts for individual). Socio-technical systems theory is a further development, which incorporates an explicit theory of organisation by extending the unit of analysis from the individual worker to the primary production unit. The various theories of job design consider similar job characteristics to be significant. However, by considering the organisation of work above the level of individual worker's jobs, socio-technical theory encourages more radical solutions than the other job design theories.

Socio-technical theory was initially synthesised from the findings of two major studies carried out by researchers at the Tavistock Institute, in Durham coal mines and in an Indian textile mill. Klein (1994) identifies four concepts arising from this work:

i. The technical and social systems are interdependent. They influence each other in both directions.
ii. There is choice in the way one organises production around any given technology.
iii. The work system is an open system.
iv. There is choice in the way technology itself is designed.

A set of hypotheses for effective ways of putting tasks together to form jobs was developed by researchers of the Tavistock Institute (Buchanan 1979; Hill 1971). These are based on satisfying the main psychological requirements of jobs: variety (other than novelty) and challenge (other than physical), continuous learning, a discrete area of decision making, social support and recognition, relationship between work and social life, and belief in a job as leading to a desirable future. Psychological requirements of jobs are in turn derived from human needs for affiliation and supportive social contact, achieving and maintaining a favourable self concept, influence and control over one's environment, satisfying curiosity, social and economic security. The resulting job design hypotheses are as follows:

i. An individual's work should provide the following: optimum variety; a meaningful pattern (ie. whole tasks); optimum work cycle length; scope for setting output and quality standards, with feedback of results; inclusion of preparation and auxiliary tasks; for the use of valued skill, knowledge, and effort; some perceivable contribution to the utility of the final product.

ii. Where jobs are interdependent, stressful, or do not individually make perceivable contributions to the utility of the final product they should be grouped together: to provide for job rotation; physical proximity; approximate an overall task; provide scope for setting standards and receiving feedback; provide some control over the boundary tasks.

iii. Generally, work organisation should also provide channels of communication to allow workers requirements to be incorporated in the design of new jobs, and provide channels of promotion.

The multi-disciplinary experiments at Phillips aimed at resolving problems of quality and morale (van Beek 1964), and the experiments in industrial democracy at Volvo, conceived to create a better working environment to reduce the cost of labour turnover and absenteeism (Berggren 1993; Ellegård et al 1992; Rehder 1992; Willatt 1973), are two important examples of flow-line reorganisation. Both involved breaking down the production line, restructuring of task content towards the creation of whole jobs, and decoupling major process stages with small buffer stocks. The Volvo experiments also included the formation of autonomous flexible work groups. Although some commentators (Prokesch 1991; Womack, Roos and Jones 1990) have dismissed Volvo's experiments and hailed the closing of its most innovative factories as evidence of their failure, it appears they were rather short sighted. Nissan, Toyota, Honda and Mazda are all now exploring similar concepts to those that were employed by Volvo (Berggren 1993; Rehder 1992).

Despite the empirical success of the human relations and socio-technical approach to work organisation, some researchers doubt the validity of the theories on which they are based. For example, Wall (1984) suggests that productivity enhancements thought to flow from improved employee motivation are in fact mainly due to improved labour flexibility, mobility, and ability to use initiative, and on reduced indirect costs. Kirosingh (1989) expresses a similar view. Kelly (1982) proposes a contingency theory of job design. This states that where the factors prompting the use of job design involve personnel problems, ie., poor morale, absenteeism or turnover, then the mechanisms of performance improvement posited by classical job design theory will explain performance. On the other hand, where job design is prompted by other sources, such as markets or the production system itself, then more conventional reward and control systems, ie., job structure, supervision, pay and other controls will explain performance improvements. His detailed analysis of the job design literature provides significant support for the latter hypothesis and therefore his contingency theory.

2.1.3 Alternative Terminology

The fragmented development of cellular manufacturing as described above has given rise to a confused terminology. Various other expressions can be found which combine the notion of small groups or subsystems with an expression for a means of production. For example, Jackson (1978) refers to the cell system of production, which comprises the cell system of manufacture and the cell system of assembly. Ross (1991) distinguishes modular manufacturing as being more people oriented than cellular manufacturing. Other researchers concerned with the human element of the production system have produced a different set of terminology again, emphasising the nature of the work done, eg. group working, self organised groups, and autonomous work groups. All these concepts have fundamental similarities. This research has therefore drawn upon the whole related body of work.

The relationship between group technology and cellular manufacturing, in particular, is a point of confusion that requires some further explanation. As discussed in section 2.1.1, Mitrofanov described his work on component grouping as group technology, and Burbidge expanded Mitrofanov's initial ideas into a complete system of production. While Burbidge retained the term group technology, some researchers felt the need to differentiate between the formation of component families to be produced at the same set-up of a single machine, and the formation of a group of different machines that could complete the manufacture of family of components. Edwards (1971) proposed the general term "cellular systems", to describe systems of the latter type, after Astrop's (1969) more specific "Serck Audco Cell System of Batch Manufacture".

Following a similar path to Edwards, US researchers have since expanded the term group technology to mean a wider philosophy concerned with the general exploitation of similarities within groups. Cellular manufacturing is then, the application of group technology to the direct production resources (Greene and Sadowski 1984; Hyer and Wemmerlöv 1984). This is illustrated by the APICS dictionary (APICS 1987) definition, where group technology is given as, "An engineering and manufacturing philosophy which identifies the "sameness" of parts equipment or processes. It provides for rapid retrieval of existing designs and anticipates a cellular type production layout."

Ironically, it appears that cellular manufacturing has become the dominant term because it is more descriptive of the holistic manufacturing concept intended by Burbidge (eg. incorporating production control, job design etc.), and more generally applicable (eg.

includes assembly) than group technology, which is too readily associated with its roots in component analysis (Edwards 1971; Schonberger 1990; Sinha, Hollier and Grayson 1980).

Despite the fact that cellular manufacturing has become the dominant term, several authors have not adopted it. Burbidge (1979, 1991, 1994[a]), actively discouraged its use, suggesting that cells are somewhat smaller clusters of equipment than a group technology "group", and that they are unlikely to be able to undertake all the processing required to complete the products that they make. However, this definition does not correspond with the cellular manufacturing literature (Black 1983; Offodile, Mehrez and Grznar 1994), and it is the authors experience, that compromise during cell design is the main reason for cells not completing their products, rather than differences in understanding of the fundamental nature of cellular manufacturing.

The net result is confusion, as group technology is frequently, but not consistently, used synonymously with cellular manufacturing. The author recognises the value of Edwards' distinction between group technology and cellular manufacturing. Following his convention, cellular manufacturing refers to a system for organising production that exploits self sufficient groupings of production resources that can complete a defined family of parts. This thesis is concerned with cellular manufacturing as defined above and adopts the cellular manufacturing terminology. However, the research has drawn upon all the literature relevant to this concept regardless of the terminology used.

2.2 A Unified Concept of Cellular Manufacturing

The modifications being made to flow-lines described in section 2.1.2, made them more like the manufacturing cells that were being designed to emulate them within the constraints of low volume/high variety environments. The widespread use of autonomous group working connects socio-technical systems theory with cellular manufacturing. Pasmore (1988) for example, identifies the use of autonomous work groups in 53% of 134 reported socio-technical redesign cases. Klein (1994) however, is careful to point out that autonomous work groups are not the only possible solution to socio-technical systems design and should not be treated as a panacea. Moreover, she notes that autonomy is not the only design criterion, and in some situations, may not be the first priority. These arguments are also supported by Alder (1994). Buchanan (1979) identifies group technology as a technical solution to a production problem, where the term group refers to a group of similar products. He indicates that group technology does not imply autonomous group working but is a technically advantageous way of organising batch manufacturing that affords the opportunity to establish autonomous group working. More recently however, Buchanan (1994) describes cellular manufacturing as an emerging *'socio-technical package deal'* of related and mutually reinforcing physical and organizational innovations. Huber and Brown (1991) also find cellular manufacturing to be compatible with socio-technical theory.

The two broad areas of research have been fairly pragmatically assimilated to provide a unified concept of cellular manufacturing. The benefits of a motivated work force are commonly cited alongside the benefits of simple material flow, reduced WIP, and improved accountability. The manufacturing system features associated with cellular manufacturing are compatible with both theories. Cellular manufacturing is also now a commonly used term in assembly as well as component production (Bennett and Forrester 1993; Burbidge 1989; Jackson 1978).

2.3 Cellular Manufacturing and Process Position

Process position provides a framework for understanding the fundamental nature of production systems and the relationship between them. Hayes and Wheelwright (1984) and Hill (1985) indicate that the overall determinant of the way production should be organised is the nature of demand. Several distinct process choices can be identified along a continuum of increasing volume and variety. For example, Hill identifies five classic processes: project, jobbing, batch, line and continuous production. A more precise classification is given by De Toni (1992), which separates those production systems that are determined by the nature of the product (discrete products from bulk or dimensional products) from those which are determined by the way in which the production volume is obtained (single, batch and flow production). Moving from single towards flow production involves investing in the manufacturing process to reduce some of the variable costs of production. Versatility is usually lost as the manufacturing is made increasingly efficient by tailoring it towards the production of a specific and narrowing range of products. Consequently, these products are required in greater volumes to carry the process investment.

Bennett and Forrester (1993) develop this idea to show how it relates to options for facilities layout (ie. fixed, by function and by operation sequence) and options for the organisation of work (ie. product, process and task specialisation). They consider cellular manufacturing to be a hybrid production system. That is, one which combines different aspects of the traditional production systems in order to obtain a set of performance trade-offs that are more appropriate to today's environment than those of traditional manufacturing systems.

Figure 2.3 shows cellular manufacturing as a flexible, product focused work organisation, in conjunction with a fast throughput, product focused layout. By using flexible labour to integrate and smooth the load between operations, cellular manufacturing increases the range of demand stability in which it is feasible to use an operation sequenced layout and achieve continuous processing of products. Flow-line manufacturers that need to increase their flexibility in the market place can therefore look to cellular manufacturing to provide that capability. On the other hand, such flexibility provides an alternative to functional layouts and batching in the mid range of demand volume and variety, if products with similar processing requirement can be grouped together for production in a cell. Thus the benefits of rapid throughput times and low work-in-progress associated with flow-line manufacturing can be achieved in a demand environment that would traditionally necessitate batch manufacturing. Schonberger (1986) summed this up nicely, "High-variety, low-volume manufacturing is repetitive; we simply failed to organise it that way." (p. 112). Cellular manufacturing can therefore be seen as providing an alternative to functional and flow-line organisations, that bridges the gap between small batch and mass production.

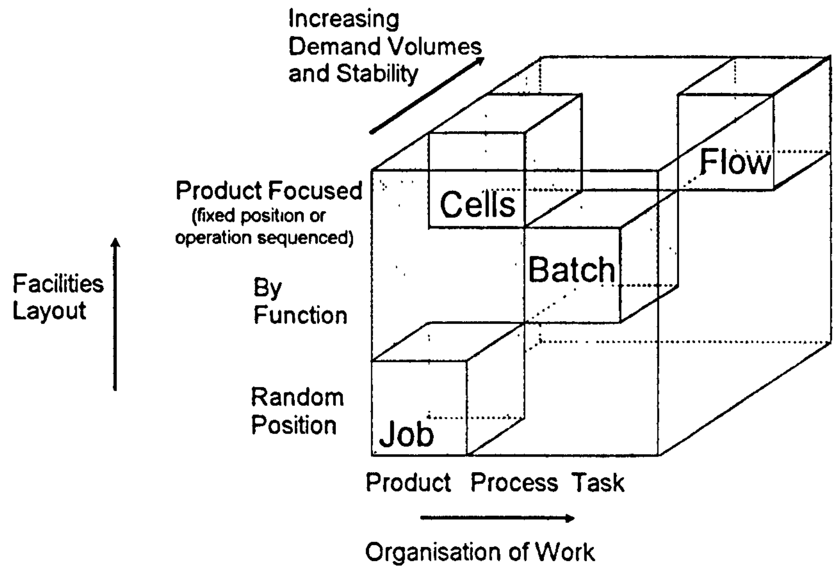


Figure 2.3 Relationships Between Traditional and Cellular Manufacturing Systems
(Source: adapted from Bennett & Forrester 1993 p.44)

2.4 Variations in the Organisation of Cellular Manufacturing

The distinction between organisational forms is not as clear cut as described in section 2.3. There are degrees to which layout and work organisation can be product focused, to provide a cellular organisation that approaches the ideal of an uninterrupted flow of work through the cells. In this way cellular manufacturing provides a scalable system that can be configured to suit specific demand patterns. Examples of variation in inter-cell material flow, intra-cell material flow, work organisation and cell autonomy are considered below.

2.4.1 Variations in Inter-cell Material Flow

There are a range of options for partitioning the production process in to cells. Two fundamental options: parallel and serial cells are identified in Figure 2.4. These can then be combined as required by the processes and skills necessary to make the product and to achieve the desired volume of output.

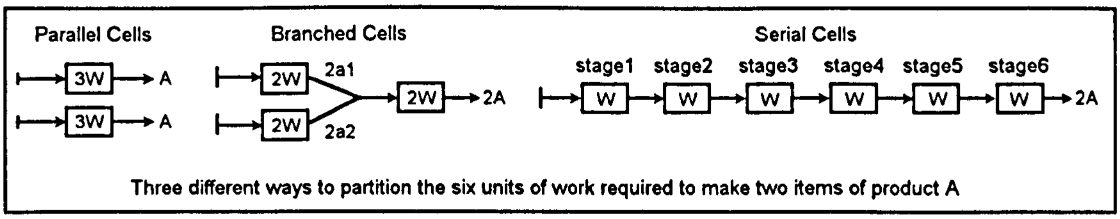


Figure 2.4 Variations in the Partitioning of Work Between Cells
(Source: adapted from Burbidge 1989, p.131)

Parallel processing provides a robust system, as duplicate lines can keep going in the event that one breaks down. Accountability for the production of whole products is contained within a cell. No inter-cell transfer times are incurred and there are no opportunities for balancing losses. On the down side, duplicate equipment may be required and operators will need a wide range of skills. Serial processing can be used to separate special skills and processes, such as electrical and mechanical, or fundamental process stages, such as material processing, component manufacture and assembly. Reducing the range of technologies in a cell, reduces one aspect of the complexity of cell management, but fragements accountability for producing a product, complicates inter-cell co-ordination. It may also increase material handling, and create balancing problems that will , reduce flexibility, and increase vulnerability. Combining parallel and serial processing gives rise to various forms of branched processing. Because different parts of the same product are produced at the same time, branched processing reduces the elapsed processing time.

Given that it is necessary to split the manufacture of a product into at least a small number of serial stages, Burbidge (1989) asserts that the material flow should be organised such that there is no back flow of material between major processing stages, and no cross flow between cells with a major processing stage. Figure 2.5 shows that there is still scope for variation in inter-cell material flow. Both systems comprise cells that complete the production of their defined family of products. However, while the cells of the left hand system supply those products to several other cells in the subsequent stage of manufacture, in the right hand case it has been possible to dedicate subassembly and component manufacturing cells to single end products.

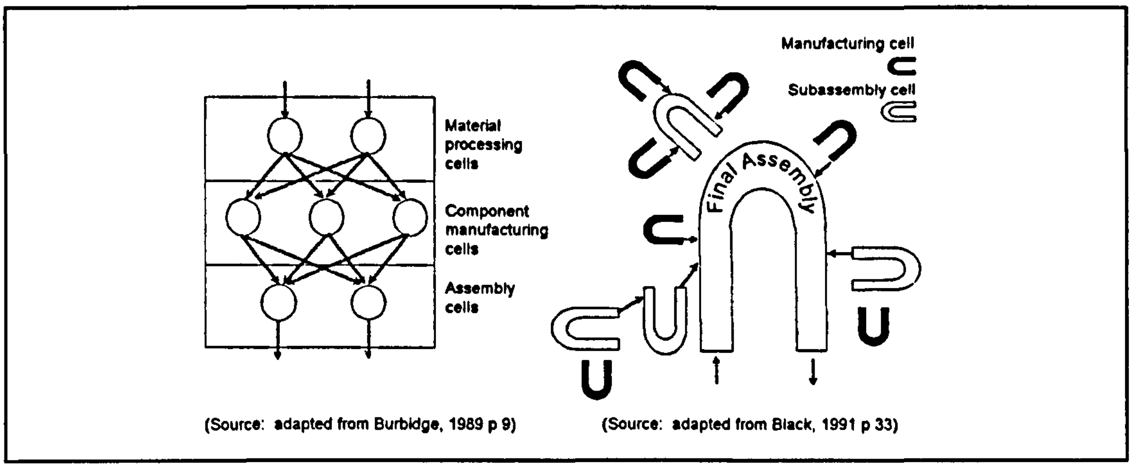


Figure 2.5 Variations in Inter-cell Customer-Supplier Relationships

The system with dedicated suppliers simplifies material flow and prevents conflict between different customers' requirements. However, apart from manual assembly processes it might not be possible to set up supplier cells with low enough capacity to match the demand created by a single customer. This could result in duplication of machinery and poor utilisation to create several cells to produce similar components for different final assembly cells. To combat this, supplier cells may have to produce more of the components required for a particular assembly cell, which would decrease the similarity among the supplier cell's product family. Such cells will also be more vulnerable to fluctuations in demand for the final product.

2.4.2 Variations in Intra-cell Material Flow

Basu, Hyer and Shtub (1994) suggest that there is a spectrum of possible cellular manufacturing systems between batch and flow-line production, as shown in Figure 2.6. Logical (or virtual) cells refer to the dedication of resources to a product family without actually collocating them. Hybrid cells are systems of physical cells in which some cells share limited resources. Physical cells are those where the necessary resources required to complete the production of the product family have been collocated.

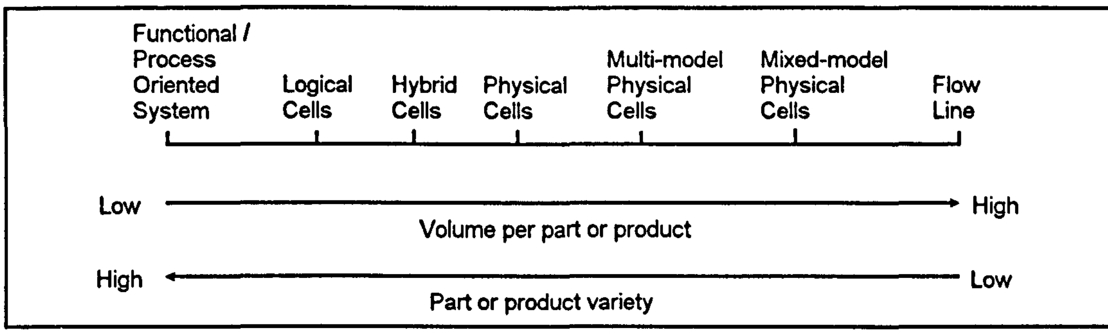


Figure 2.6 Variations in Intra-cell Material Flow
(Source: adapted from Basu, Hyer & Shtub 1994 p. 78)

As the variety the cell has to handle decreases, it becomes possible to arrange equipment according to the dominant operations sequences within the cell. Towards the right hand side of the spectrum, the internal layout of the cell is completely product oriented (either fixed location or process sequenced) such that material flow through the cell is unidirectional. This simplifies shop floor management and control and makes it easier to keep work moving through the cell.

2.4.3 Variations in Work Organisation within the Cell

Work within a cell can also be arranged in various ways in each cell depending on such factors as the size and complexity of the product, the extent of multi-skilling within the cell, and the volumes that are required.

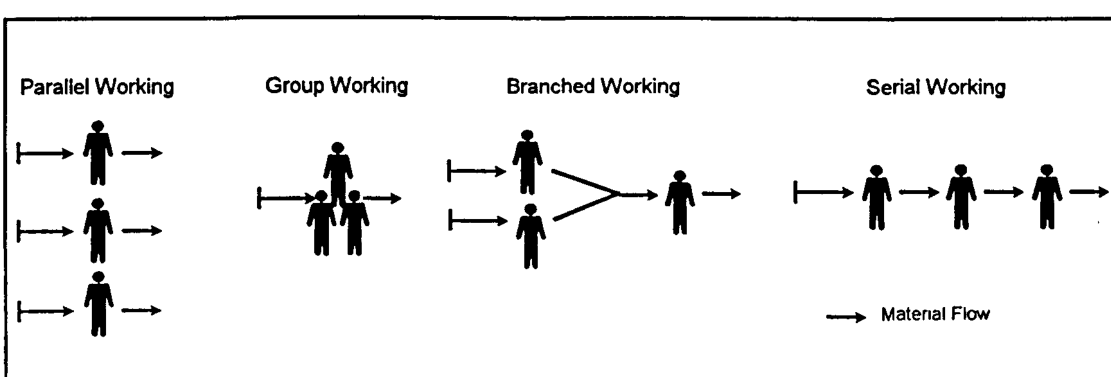


Figure 2.7 Variations in Work Organisation Within a Cell
(Source: adapted from Burbidge 1989 p.132)

Figure 2.7 shows four ways of dividing work between cell members, ranging from the situation where a worker undertakes all the operations a product requires within the cell, to the division of a product's manufacture into several serial stages each to be undertaken by a different person. Parallel and group working are both flexible with no balancing problems or inter-operation handling time and costs. Parallel working does however, require completely multi-skilled operators and is easier to implement with simple products. The other forms of work organisation can all be used to segregate skills requirements. Operators with narrower ranges of skills can then be employed, though this will inevitably reduce the flexibility of the cell. Group and branched working can also compress lead times. The sequential stages in serial and branched working create the problem of balancing and may make for less satisfying jobs. Team identity should however, temper the effect of reduced individual accountability at this level of the organisation.

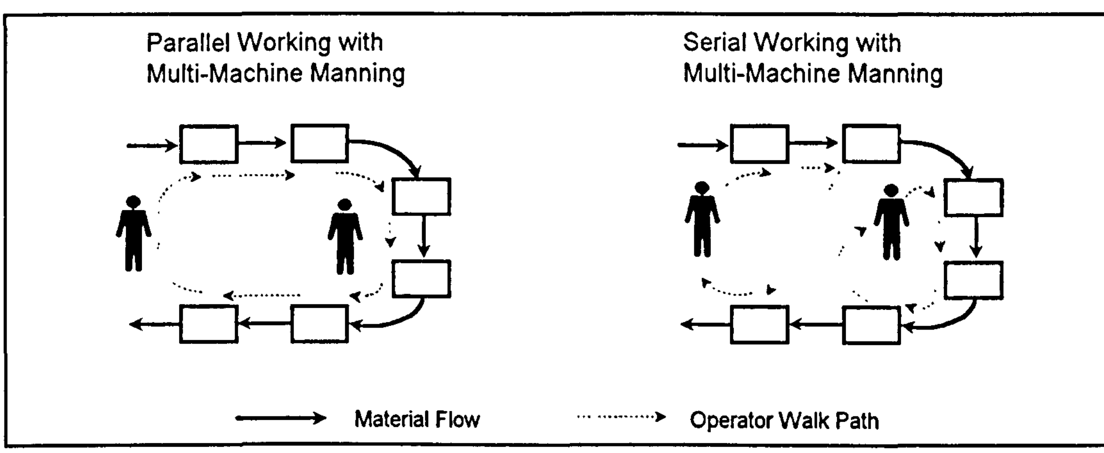


Figure 2.8 Parallel and Serial Working with an Operations Sequenced Layout

The organisation of work need not be determined by the layout. For example, Figure 2.8 shows both parallel and serial working can be achieved in an operations sequenced layout. Similarly, if it is easier to produce a product at a fixed location, individuals (or teams) may each build a product independently, or the tasks could be split between the working units and have one follow another to every product.

2.4.4 Variation in the Degree of Cell Autonomy

Birchall and Wild (1974) identify six dimensions of authority and four dimensions of responsibility along which job design can vary. These are presented in Figure 2.9 below.

Dimensions of Autonomy

i.	Goals:	qualitative quantitative	iv.	Distribution of tasks.	
ii.	Performance:	decide when to work decide where to work decide when to engage in other activities	v.	Group members:	Select and appoint new members Expel unwanted members Discipline new members Train new members
iii.	Production method.		vi.	Leadership:	Internal leader External leader

Dimensions of Responsibility

i. Materials and products
ii. Equipment
iii. Work area
iv. Communications

Figure 2.9 Job Design: Dimensions of Autonomy and Responsibility (Source: Birchall and Wild 1974)

2.4.5 Implications of Variety in the Application of Cellular Manufacturing

The range of possibilities for cellular organisation described in this section begin to reveal how flexible the concept of cellular manufacturing is. According to Astrop (1975), cellular manufacturing is capable of being applied in different ways according to a multitude of different factors some of which may be unique to a give company. Nyman (1992) states, "No two cells will be the same. For countless reasons each business environment and the inherent conditions within that environment require a different approach and yield a unique end result." (p. i). This flexibility enables the use of cellular manufacturing across a broad spectrum of industry types and process positions, but it also complicates application of the concept, because it must be adapted to suit each case. To be useful to practitioners, a model of cellular manufacturing must be able to accommodate such variation. Similarly, a corresponding process for designing cellular manufacturing systems is necessary, which describes how to go about tailoring the concept to suit a specific set of circumstances.

2.5 A Generic Model of a Cellular Manufacturing System: Cellular Manufacturing Features and Their Desired Effects

While the process position model does provide some indication of the nature of cellular manufacturing, it concentrates on the structural relationships between parts, people and machines without giving much indication of how this will effect the operation of the resulting manufacturing system. It does not incorporate many of the features described in case studies of cellular manufacturing, and therefore does not address the issues raised in sections 1.6 and 1.7 regarding the need for a system wide concept of cellular manufacturing. There is only a small amount of literature available that attempts to provide such a model of the cellular manufacturing concept. For example, Burbidge (1989) defines a group technology group by an eight point checklist of features. Similarly, Black (1991) indicates eight major elements to his cellular *Factory with a Future*. These models are difficult to compare as they can describe cellular manufacturing at different levels of detail. However, they do contain different features and contradict each other in the detail of some of the features they have in common, as can be seen in the consideration of material flow structure in section 2.4 above.

Due to the lack of an appropriate model of cellular manufacturing, a review of the literature has been undertaken in order to collate the majority of significant cellular manufacturing features, and their desired effects. The following section describes some of the characteristics of cellular manufacturing revealed by the literature review. The full list of features and their effects is presented in Appendix A.

Cellular manufacturing can be considered to be a system of production (Sinha, Hollier and Grayson 1980). IDEF0 process modelling notation provides a structure for describing the relationships between the functional elements of a production system (Bravoco and Yadev 1985; Ross et al 1980). Cellular manufacturing is primarily concerned with the function "make product" but also affects interfacing functions, as shown in Figure 2.10. This framework has been used to structure the features of cellular manufacturing to make the list more accessible and to draw attention to the system wide scope of the concept.

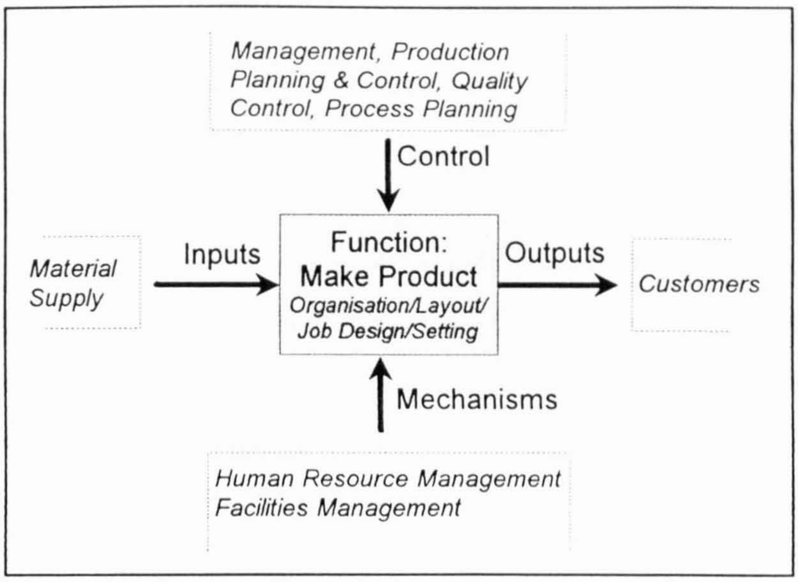


Figure 2.10 Framework for Describing a Manufacturing System

Function (Make Product)

Organisation: Cellular manufacturing groups production resources such that each cell is capable of completing the manufacture of a defined family of products. This principle extends to assigning indirect resources to the cells where they are critical to the cell being able to operate a high levels of performance. The more autonomous the cell is, the greater their accountability for cost, quality, and lead time, and the greater their, ability to take action to improve performance (Burbidge, Partridge and Aitchison 1991; McManus 1991). A compound effect on performance may also be achieved due to the increased perception of task significance (Huber and Hyer 1985) and improved morale and job satisfaction arising from this organisation (Fry, Wilson and Breen 1987; Greene and Sadowski 1984).

Dedicating resources to specific products reduces process variables and has many advantages. Consistency of production is improved (Fry, Wilson and Breen 1987; Moreton et al 1993), the number of set-ups required may reduce (Dumolien and Santen 1991) and it can help reduce set-up times (Kellock 1992; Welke and Overbeke 1988). Familiarity and expertise with a given part family is also increased (Fry, Wilson and Breen 1987; McManus 1991).

Simplifying the organisation of the production system also has implications for indirect functions. Information and documentation requirements are reduced (Masom 1993; Williams 1991), process planning is less complex (Dumolien and Santen 1991; Mosier and Taube 1985), cost accounting can be simplified, and it facilitates improved cost estimating.

Layout: All the resources required to produce a family of products (including point of use storage of tools, raw material etc), are collocated, often within a clear physical boundary, and laid out to reflect the dominant flow paths within the product family. Collocation improves visibility of shortages, machine status, WIP levels etc., and reduces unnecessary material handling, and transportation, and maximises social interaction (Black 1991; Burbidge 1979, 1989; Fazackerley 1976; Greene and Sadowski 1984; Huang and Houck 1985; Lee 1987).

This enables coordination of production activities so that products can be moved quickly and directly between processes to achieve an uninterrupted flow of work through the cell. Writing about plant configuration Schonberger (1982) declared "Simplify and the Goods Will Flow Like Water." Reduced transport times means faster set-ups, shorter lead times and lower transport costs. Less transport also means less risk of damaging products while transporting them between processes (Jackson 1978). Improved communication between consecutive processes facilitates problem solving and process improvement (Lee 1987; Schonberger 1986).

Job Design: Jackson (1978) emphasises the benefits of team working that are brought about through cellular manufacturing. He writes, "The cell system of production is based on the group working principle, where a small number of people come together to function as a cohesive group, recognising that they are a group, and interacting to accomplish a common whole task." (p. 18). The cellular structure makes customer/supplier relationships explicit, and focuses the manufacturing task of each cell. A dedicated team learns to work together to achieve their common objective, and they grow to understand the special problems associated with their products and equipment (Burbidge 1979).

Multi-skilled operators and flexible team working provide the necessary operator mobility between tasks to balance work loads or to reduce labour costs through multi-machine manning (Bennett and Forrester 1993; Steudel and Desruelle 1992; Stoner, Tice and Ashton 1989). Black (1991) and Koelsch (1992) explain how volume flexibility is achievable by adjusting manning levels. Team working can also contribute to set-up reduction (Shingo 1985), and is a major lever for problem solving and continuous improvement. (Schonberger 1986, 1990). Operators can also perform the majority of material handling within the cell to reduce queuing and handling (Stoner, Tice and Ashton 1989; Welke and Overbeeke 1988).

Work is arranged so that cell operators can vary the tasks they perform and their pace of work within the limits of the overall production targets. This minimises losses arising from all operators having to work at the pace of the slowest worker at any given time. It also provides scope to rectify problems without either stopping related processes or passing on defective parts (Bennett and Forrester 1993; Burbidge 1989; Jackson 1978).

Independence, product focus, and self determination provide job variety, a sense of purpose, job satisfaction, and fulfil the psychological needs of its members. This is expected to lead to increased commitment, reduced absenteeism, and reduced labour turnover (Burbidge 1979; Jackson 1978; Stoner, Tice and Ashton 1989).

Setting up: Reduced set-up times is an important requirement for cellular manufacturing because it enables small batch sizes which smooths the load on cell resources. Costs and response to customer demand are also improved, as small batch sizes allow a wide variety of parts to be made frequently and permit reduced work-in-progress. Confining the number of parts and the differences in their processing requirements that are routed to each machine, can reduce the frequency with which setting-up is necessary, and also enables the application of SMED set-up procedures to reduce set-up times. (Black 1991; Dumolien and Santen 1983; Morton et al 1993; Stoner, Tice and Ashton 1989).

Mechanisms

Facilities: A cell should have all the machines and equipment it requires to complete the manufacture of its defined family of products (Burbidge 1989). This objective will be facilitated by a policy of buying multiples of small machines in preference to large machines. In addition this approach to capacity provision can allow dedicated machine set-ups, will reduce the impact of breakdowns, and will increase the opportunity for operators to perform in-cycle operations (Schonberger 1983; Stoner, Tice and Ashton 1989).

A defined range of products allows accurate specification of equipment, rather than the expense of having all machines meet the highest requirements of all the products. Investment in jigs and fixtures can be kept low by designing them for the product family rather than for individual products (Gallagher and Knight 1986; Jackson 1978; Noaker 1993). Standardised tooling can also help to reduce set-up times (Morton et al 1993). Similarly, a defined range of products and reduced WIP allows for the development of customised handling devices. These can reduce handling and damage and can also be incorporated into the shop floor control system (Omand 1992; Welke and Overbeeke 1988)

With the reduction of routing flexibility associated with cellular manufacturing, the provision of reliable capacity is essential. Moreover, eliminating the unplanned delays resulting from machine breakdowns will remove one of the reasons why WIP is necessary. Total productive maintenance and preventative maintenance are both identified as valuable elements of a cellular manufacturing system. Devolving responsibility for maintenance to the cells can provide the necessary additional resource for extra routine maintenance. Schonberger (1986) notes that this has the additional advantage of enabling these tasks to be performed in cycle. Devolved maintenance also increases ownership and morale, and improves feasibility of maintenance scheduling (Morton et al 1993; Noaker 1993; Stoner, Tice and Ashton 1989; Welke and Overbeeke 1988).

Good housekeeping is akin to maintenance, and can also be made the responsibility of cell operators. Keeping things clean and in a designated place improves quality, safety, and maintenance, reduces unnecessary operator motion and searching, and provides visual control of such things as tool availability and WIP level. It also can assist marketing and improve industrial relations (Black 1991; Masom 1993; Morton et al 1993).

Human Resources: Responsibility for the complete production of a family of products (or a significant portion of larger products) is consolidated within a defined team of people, who are multi-skilled, flexible, and work together to achieve production objectives (Astrop 1969; Bennett and Forrester 1993; Burbidge 1979; Jackson 1978).

Achievement of multi-skilled, flexible team working requires increasing the amount of time spent on training (McManus 1991). Skills that are not directly related to the manufacturing process might need to be provided, such as interpersonal skills and problem solving skills (Huber and Brown 1991). Responsibility for training can be devolved to the cell to increase ownership of the resources and to ensure that appropriate training is received. Job grades may also be reduced to encourage flexible working (Peters 1989).

Reward systems should encourage behaviour that is appropriate to the performance objectives and desired working methods for the cellular manufacturing system. For example, paying for knowledge or skills (Huber and Brown 1991; McManus 1991; Peters 1989) to encourage multi-skilling, and paying team based rewards (Welke and Overbeeke 1988) to encourage team working. At a minimum the reward system should not encourage adverse behaviour. Therefore piece rate systems are generally considered to be inappropriate, while simple systems such as flat rates and salaries are considered to be acceptable (Burbidge 1979; Schonberger 1986; Stevens 1987)

Product focused organisation provides a good environment for developing competent managers, and therefore a clear route for promotion from the shop floor (Burbidge 1989).

Management and Control

A cell has the necessary capability and responsibility for the complete manufacture of their products. This results in a high degree of accountability, which will itself improve performance (Sirota 1973). It also makes it possible to consider each cell as a mini-factory, and to manage them as such. The problem of managing production is thereby simplified in two ways: first, planning the work flow requires only that work is planned into and out of the cell, rather than through each process in the cell; second, monitoring the behaviour of the cell effectively monitors the behaviour of all the people within the cell (Lockyer 1983).

Accountability plus a simplified management task make it possible to locate responsibility and authority for many aspects of production management to the cell, such as: scheduling and due-date conformance, cost, quality control, performance measurement and continuous improvement. This, facilitates appropriate and rapid response to changing circumstances, leading to more reliable production, and will also reduce indirect labour costs (Burbidge 1989; Schonberger 1986). The cell is then the lowest level of detail considered by the factory management, which provides instruction, targets, and feedback, and monitors performance of the cells rather than the individual people and processes within the cell. Demand is therefore in terms of products rather than operations. Performance measures and incentive systems should reflect the objectives of cellular manufacturing and include drivers of customer satisfaction. Direct communication between a cell and its customers and suppliers is encouraged (Bennett and Forrester 1993; Burbidge 1979, 1989; Harrison 1992; Kellock 1992; LE&S 1988; Mechanical Engineering EDC 1975; Prickett 1993; Schonberger 1986). Warnecke's (1992) fractal factory takes this a stage further advocating that fractals should also play a part in developing their own objectives.

Production Planning and Control: As mentioned above it is possible to devolve operation scheduling and control to the cell. Considering the cell as a single planning point vastly simplifies the job of planning and controlling the flow of material to and from cells, making it quicker and more effective (Kumar and Hadjinicola 1993; Love and Barekat 1989). On the shop floor, the clear material flow and limited product range simplifies scheduling and material tracking, allowing the use of low cost visual and physical control systems. Increased responsibility and better visibility of plans and progress in the cell can provide opportunities for presetting and set-up dependent sequencing, reduce WIP, increase operators commitment to the plan, increase operator satisfaction, and reduce administration costs (Deeming 1993; Fry, Wilson and Breen 1987; Kellock 1992; Oliver 1991; Prickett 1993; Steudel and Desruelle 1992).

WIP is kept to a minimum and contingencies in the system are provided instead, by spare machine and labour capacity and labour flexibility (Oliver 1991). This reduces queuing, space requirements, handling, damage, and obsolescence. Production planning and control is simplified, and administration is reduced. (Burbidge 1989; Kumar and Hadjinicola 1992; Masom 1993; Schonberger 1986; Stoner, Tice and Ashton 1989) Low WIP also makes systems deficiencies more visible and encourages their rectification (Schonberger 1986; Taheri 1990). Low WIP and small batches speed up performance feedback and increase an organisation's ability to control its processes (Oliver 1991). For example, by reducing the interval between defect creation and detection, less defects are produced before a faulty process is discovered. Small batch sizes and levelled scheduling help to enable low WIP operation (Harrison 1992; Kirton and Brookes 1994).

Short lead times simplify the job of marketing, production planning, and purchasing, and reduce the need for expediting throughout manufacturing. To keep costs low, processes and manning levels for these functions should reflect the simplicity of their task (Black 1991).

Quality: In keeping with cellular manufacturing's principle of maximum ownership, cells are usually responsible for the quality of their own products. This often incorporates some form of source inspection . Source inspection allows quality to be assured at each step of the process, and for any rework or corrective action to take place at its point of creation. If operators inspect their own work in cycle, or inspection is built in to the process, using poka-yoke devices (Shingo 1986), every item can be inspected, without consuming lead time or incurring extra costs. Source inspection, reduces the number of defects produced before a processing error is discovered, and increases the information available to assist with identifying and rectifying a problem. It also reduces the likelihood of passing defective items onto down stream processes, so resources are not wasted processing them, and the need for rework or replacement is identified early (Deeming 1993; Dumolien and Santen 1991; Fry, Wilson and Breen 1987; Nyman 1992; Schonberger 1986; Stoner, Tice and Ashton 1989).

Process planning: The focus and reduction of routing alternatives with a cellular organisation simplifies process planning activities and makes prediction of new product manufacturing costs more accurate (Dumolien and Santen 1983). Where a new cell is to be used for a new product, the introduction of that product is greatly simplified. The cell can be developed alongside the product. This isolates the disruption caused by new work while still enabling processing problems to be discovered and solved before production volumes are ramped up (Nimmons, Williams and Cursham 1994).

Inputs

The way in which material is provided to the cell must match the way it is consumed by the cell otherwise the result will be shortages or WIP accumulation, or both. Cells should therefore be responsible for the level of their WIP and be able to regulate the supply of material to match their immediate production requirements (Schonberger 1983, 1986). Call-off (Burbidge 1990) and kanban (Esperrago 1988) are two examples of appropriate execution mechanisms for instructing downstream processes to supply material. Because each cell has a defined product range and therefore material requirements, it is possible for material to be delivered directly to the cells. This clearly associates excess material with the cell responsible, it also eliminates delays and wasteful handling and storage operations, and provides the opportunity for direct communication between cells and their suppliers (Hall 1982; Masom 1993; Schonberger 1982).

Outputs

Production rates are aligned with customer demand such that products are made only as they are required by the next stage in the supply chain (Black 1991; Burbidge 1961, 1989; Schonberger 1986; Wemmerlöv 1988). Direct contact with the customer is encouraged as this increases perception of job significance (Passmore 1988).

Summary

In summary, cellular manufacturing is achieved by grouping labour, facilities, and products, such that, semi-autonomous teams of multi-skilled and flexible people each have all the resources necessary to complete the manufacture of a defined family of products through a major processing stage. Cellular manufacturing exploits this simple structure, clarity of purpose and empowered workers, to achieve fast throughput times, and reliable quality and delivery, for a variety of products, using simple, efficient processes of operation and management. This is illustrated in Figure 2.11.

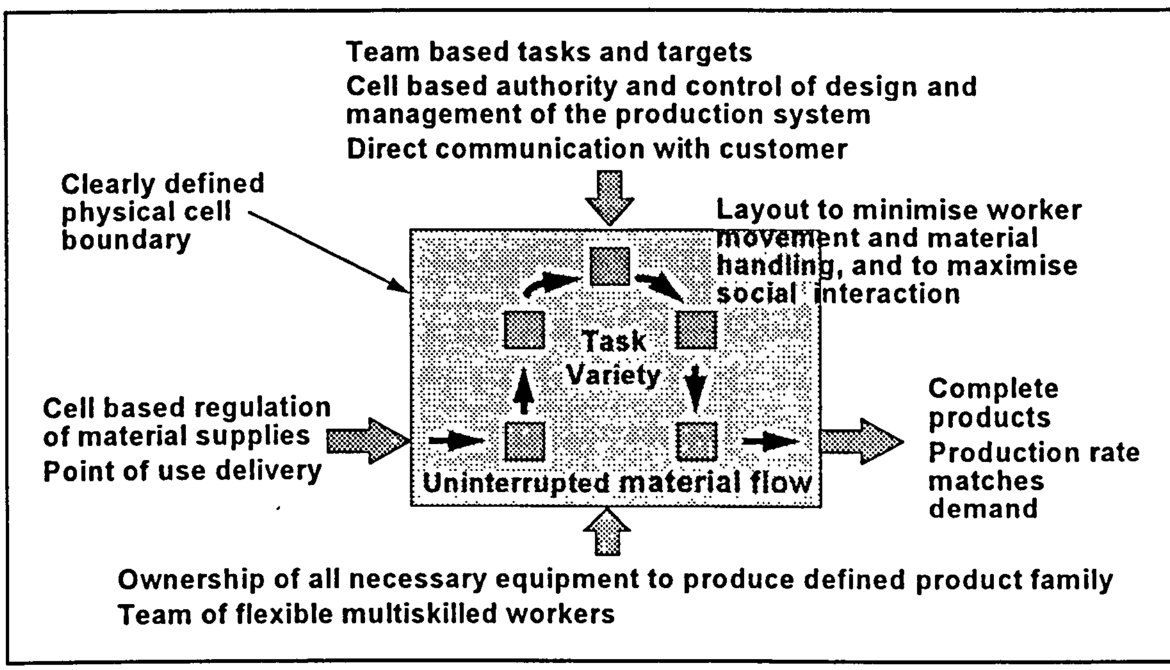


Figure 2.11 Summary of Generic Model of a Cellular Manufacturing System

A large collection of features commonly associated with cellular manufacturing and their desired effects are presented in the discussion above, and in Appendix A. The extent of cellular manufacturing across the production system is apparent as is the complex nature of the interrelationships between the various features and their effects. Figure 2.12 begins to shows the complex ramifications of the features of cellular manufacturing (as depicted in Figure 2.11) on the main generic strategic manufacturing goals of cost, quality, lead time, delivery dependability, flexibility and continuous improvement.

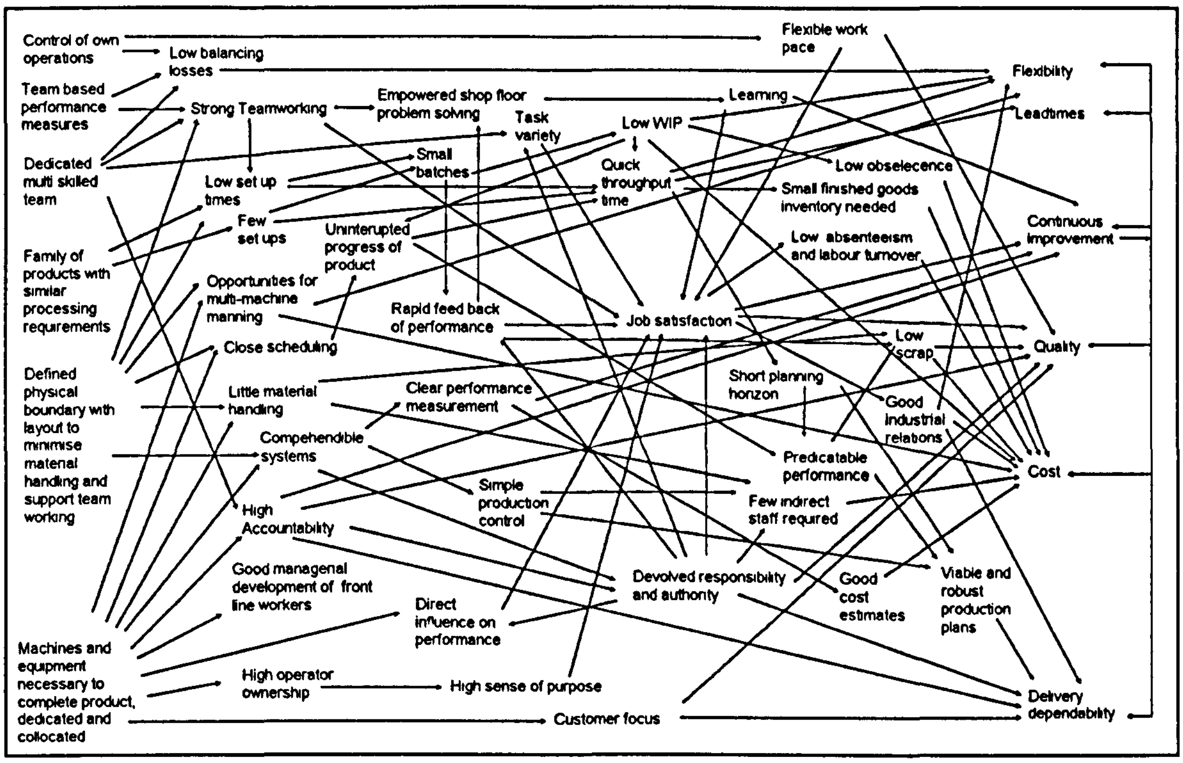


Figure 2.12 Ramifications of the Features of Cellular Manufacturing

Not all features have a direct effect on performance, but they are incorporated in order to enable other features, or to mitigate their undesirable side effects. For example, paying for skills encourages multi-skilling which in turn enables flexible working. Some perform both functions. For example, moving sequential processes close together will initially only have a small effect on lead time and transport costs, but it enables batch size reduction. The extra visibility and communication enable local production control and enhances problem solving. The broad scope of cellular manufacturing and the interrelationships between its features and their effects makes it difficult to find a framework to structure these components.

The case material from which the above model was derived all emphasise different features and effects as being important to their success. Variation is also revealed in the detail of how the same features are applied in different cases. This confirms that cellular manufacturing is a flexible concept that can be tailored to suit the specific objectives, and situation to which it is being applied. It also reinforces the value of an accepted system wide model to represent the general case of cellular manufacturing

2.6 Undesirable Effects of Cellular Manufacturing Features

The most commonly cited disadvantages of cellular manufacturing are, cost of machine duplication, cost of rearranging facilities to accommodate new products, lower machine utilisation, reduced routing flexibility, and vulnerability to equipment breakdown (Greene and Sadowski 1984; Lee 1987; Steudel and Desruelle 1992; Wemmerlöv 1988). Jackson (1978) also warns against allowing teams to become too insular such that inter-cell rivalry becomes a barrier to factory performance. Multi-skilling will incur higher training costs and practitioners often expect the cellular layout to require greater floor space. However, the role of many features of cellular manufacturing appears to be to mitigate some of the undesirable side effects of other features. Wemmerlöv, suggests that if systems designers are aware of the potential disadvantages, and have a clear view of what is to be accomplished by the cell system, then the disadvantages can often be avoided or knowingly accepted. His point of view is supported by the case and survey evidence cited in section 2.5 and section 1.5 respectively, some of which even report cellular manufacturing as having a positive impact on certain of the above mentioned issues. An example is provided by Herbert (1992), who describes how a brush manufacturer changed the structure and management of its cellular manufacturing system to make better use of limited resources and to eliminate inter-cell rivalry.

2.7 Conclusions

The literature describing cellular manufacturing is fragmented and the concept has not been well defined to date. This inhibits understanding, communication, and application of the concept. The following conclusions have been drawn from the review of the nature of cellular manufacturing presented in this Chapter.

- Cellular manufacturing is a system wide concept. Many changes are required throughout the manufacturing system to make the self sufficient, product focused structure of cellular manufacturing feasible. Similarly, many opportunities arise to change the manufacturing system to improve performance.

- Reports of cellular manufacturing implementations each emphasise a slightly different set of features, in addition to the primary cellular structure. Cellular manufacturing should not therefore be viewed as a rigid concept. A company only needs to adopt that subset of features which, are appropriate for a particular company's specific objectives and the nature of their existing manufacturing system. Moreover, the detail of the way in which features are applied can vary from case to case.

- A working definition of cellular manufacturing has been generated for this thesis:

  Cellular manufacturing is defined as a general set of mutually compatible, production system wide, features for supporting or exploiting self contained groupings of manufacturing resources that complete a defined range of products.

- This model is applied to a particular situation by selecting the appropriate subset of features for the specific objectives and constraints of that situation.

This chapter has fullfilled the first research aim to develop a system wide definition of cellular manufacturing to guide the design of cellular manufacturing systems. The concept is presented as a general set of features from which an appropriate sub set can be selected for a specific application. A useful contribution has been made by compiling a significant set of cellular manufacturing features and their effects from an extensive survey of the literature.

The ramifications of cellular manufacturing features are complex and not well understood. There are several factors contributing to this which will have a significant impact on the problem of designing a cellular manufacturing system.

- The elements of a production system are interrelated, such that introducing a particular feature of cellular manufacturing may have different effects depending on the nature of the original manufacturing system and the other cellular manufacturing features being implemented. This makes it difficult to isolate and quantify the effect of specific cellular manufacturing features. It also means that the features of cellular manufacturing can have a variety of roles. A feature could directly improve performance, enable or support other features or perform both of these functions. Therefore, several features may need to be planned and implemented together.

- There are several theoretical explanations for the beneficial effects derived from the features of cellular manufacturing. It is probable that more than one may operate in unison, and that they may operate to different extents depending on the situation to which the feature is applied.

- Cellular manufacturing is a human activity system, which results in multiple perspectives on what the systems objectives are, and how they should be achieved. Accounting for this complicates the design task. The human element in the system further attenuates the degree of determinism between features and their effects.

Cellular manufacturing is a complex and flexible concept, that can be applied in different ways according to the requirements and nature of the specific production system being reorganised. This poses a substantial design problem, which suggests that improving the process of designing cellular manufacturing systems will lead to more successful implementations. Chapter 3 reviews current approaches to designing cellular manufacturing systems.

Chapter 3 Designing Cellular Manufacturing Systems

The aim of this chapter is to develop an understanding of the process of designing cellular manufacturing systems, and determine the strengths and weakness of current methods. The theory and practice of designing of cellular manufacturing systems is reviewed and the various approaches compared. The value of current methods for helping a company to design cellular manufacturing systems is discussed, with reference to the concept of cellular manufacturing developed in Chapter 2.

3.1 Introduction

The design of cellular manufacturing systems can be described as a process. A process is a set of ordered activities to achieve a specified outcome (Davenport 1993; Harrington 1991; Hitchins 1992). A process can be understood by identifying its mission and scope, the process activities involved and its performance (Harrington 1991). Because any process can be defined in these terms, they can be used to provide a framework for comparing and contrasting various approaches to designing cellular manufacturing systems.

Due to cell formation being the most visible component of the cellular manufacturing concept, and because of the complexity of the problem, the primary issue dominating the design of cellular manufacturing systems in batch production has traditionally been part machine grouping. This body of work is reviewed in section 3.2. Section 3.3 reviews methods that go beyond cell formation to address the design of a broader cellular manufacturing concept. These methods include simple industrial engineering based methods, just in time methodologies, socio-technical systems design, and manufacturing systems engineering methodologies. The practice of designing cellular manufacturing systems is considered in section 3.4.

3.2 Part-Machine Grouping

Understanding how a company's facilities can be rearranged into cells that will accommodate the company's product range without requiring a large investment in new equipment is a considerable problem in batch production environments. Moreover it is probably the single most visible change to take place, and one of the first significant design activities tackled. For these reasons and also because the part machine grouping problem provides rich research opportunities, it has received a considerable amount of attention. An indication of the emphasis on this issue is provided by a review of the papers published in the International Journal of Production Research: approximately 70% of cellular manufacturing research published between January 1987 and July 1993 was dedicated to the development of cell formation tools (Appendix A).

The high level of research effort directed at solving the cell formation problem has resulted in the development of many procedures for part-machine grouping, based on a variety of approaches to the basic problem and employing a range of techniques. Several reviews and classifications of this body of work can be found in the literature. For example, Figure 3.1 represents the taxonomy used by Wemmerlöv and Hyer (1986) to classify seventy five contributions to the literature. This provides a useful insight into the nature of the cell formation process.

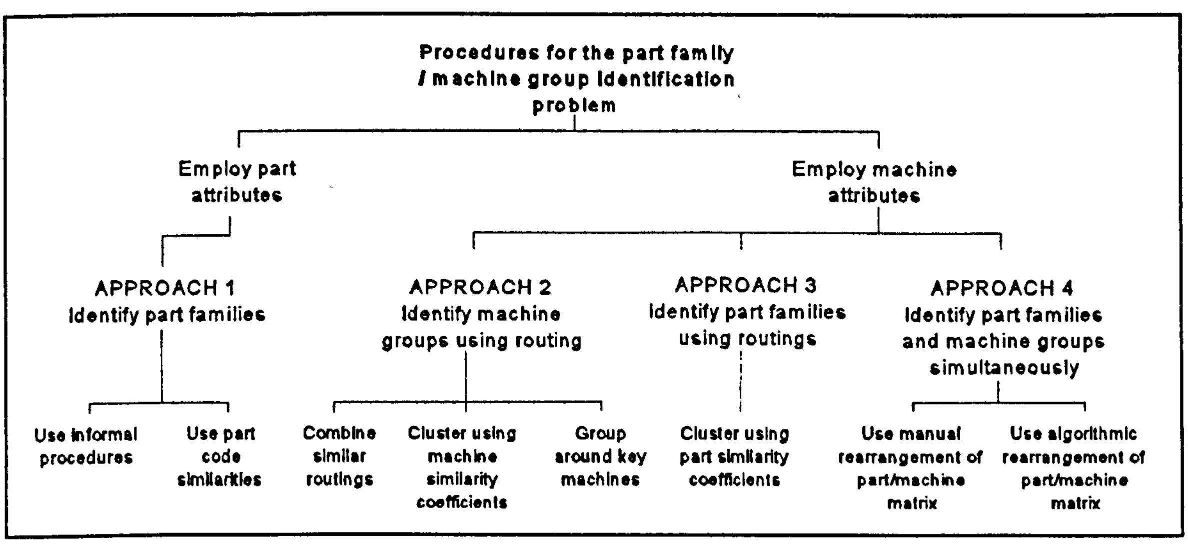


Figure 3.1 Procedure Based Taxonomy of Methods for Part-Machine Grouping
(Source: Wemmerlöv & Hyer 1986)

Approach 1

Approach 1 methods identify part families without reference to routings. Having formed part families, a second procedure will then be required to assign machines to them. This gives rise to the possibility that there will not be sufficient machines available, necessitating merging of part families with competing demands for limited numbers of machines, investment in duplicate machines, or subcontracting to avoid intercellular movement of parts that cannot be completed in one cell. Burbidge (1989), and Kusiac and Cheng (1991) also criticise grouping on the basis of part design characteristics, for bringing together parts of the same shape that should be processed on different machines, due to differences in quality requirements, volumes, etc, and for failing to group different shaped products that are produced using the same processes. Wemmerlöv and Hyer (1989) report this approach as being the most commonly used in designing cellular manufacturing systems.

The other three approaches all employ routing information in the analysis and so avoid this criticism. However, Wemmerlöv and Hyer point out that a routing based analysis will inevitably constrain the solution according to existing methods which will not necessarily be the best method of production.

Approach 2

Approach 2 methods use routing information to group machines that process similar parts. A second procedure will then be required to assign parts to the machine groups. This gives rise to the possibility, for some parts, that no cell will have all the machines necessary for their completion. As in Approach 1, cell merging, machine duplication and subcontracting can be employed to reduce intercellular traffic. Grouping of machines rather than parts can be advantageous in cases where there are very large part populations relative to the number of machines.

Approach 3

Approach 3 methods use routing information to group parts that visit similar machines. This is similar to Approach 1, except part families are based on routing similarity. Vakharia and Wemmerlöv (1990) have used this approach so that the operation sequence of products can be considered, to create cells with a high degree of unidirectional product flow.

Approach 4

Approach 4 methods identify part families and machine groups simultaneously. These procedures attempt to avoid solutions with unnecessary exceptional parts by forming the part family and the machine group simultaneously. When exceptional parts do arise, the options for dealing with them are the same as for Approaches 1,2 and 3.

A more up to date review, with a hundred and seven references is given by Offodile, Mehrez and Grznar (1994). Their classification is based on the techniques used to perform the grouping analysis, see Figure 3.2.

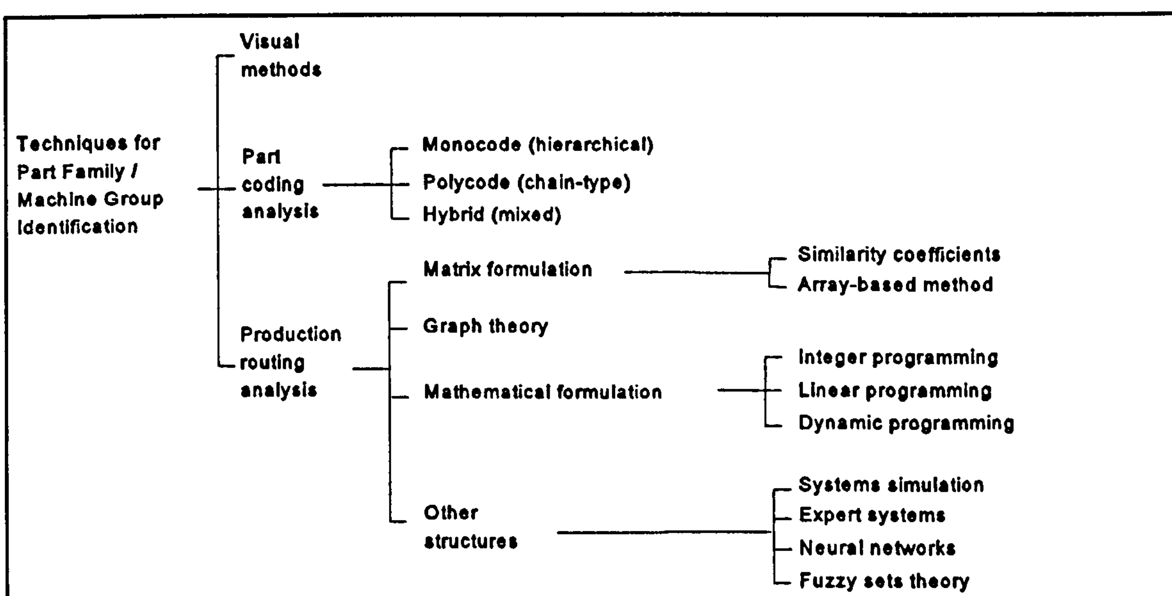


Figure 3.2 Technique based Taxonomy of Methods for Part-Machine Grouping
(Source: Offodile, Mehrez, & Grznar 1994)

Visual Methods

This is a relatively informal approach to cell formation that would fit into Wemmerlöv and Hyer's first classification: find part families without using routings. This approach can be inexpensive but relies heavily on the expertise and experience of the analyst. It is flexible in that the analyst can bring all sorts of information to bear on the design decisions as felt appropriate. For example, efforts may be made to gather together all high volume parts or parts for the same end product to ensure consistency of competitive criteria and strategic manufacturing tasks.

Part Coding Analysis

This is a more formal mechanism for taking Wemmerlöv and Hyer's Approach 1. Offodile, Mehrez and Grznar suggest that classification and coding systems are not well known in the cellular manufacturing literature. However, much of the pioneering work in Group Technology was based on classification and coding, and is still considered by a lot of the literature to be fundamental to cellular manufacturing (Guerrero 1987; Kamrani and Parsaei 1994). Classification and coding systems are reviewed by Gallagher and Knight (1986), and Hyer and Wemmerlöv (1985). Hyer (1984) reports problems with using one classification and coding system for more than one purpose. Burbidge (1989) notes that while a classification and coding system may be useful as a design engineering tool, the cost of implementation and its other disadvantages make it unsuitable as a tool for cell formation.

Production Routing Analysis

These methods of cell formation cover Approaches 2, 3, and 4 of Wemmerlöv and Hyer's classification. Offodile, Mehrez and Grznar provide a comprehensive review of the model characteristic of the cell formation procedures within this category. The model characteristics considered are presented in Figure 3.3.

Heragu (1994) also reviews part-machine grouping literature, paying specific attention to those procedures that incorporate objectives and constraints beyond the achievement of mutually exclusive cells: for example, set-up time reduction, material handling cost reduction, equipment cost reduction, direct labour cost reduction etc.

1. Model structure:
   - Matrix formulation:
     - similarity coefficient based, array (sorting) based
   - Math programming:
     - integer, linear, dynamic
   - Graph theory:
     - bipartite, other
   - Other:
     - simulation, expert systems, neural networks, fuzzy sets
2. Problem data structure:
   - Binary, weighted, either, fractional
3. Clustering problem:
   - Parts, machines, concurrent formation of part-machine groups
4. Solution approach:
   - Heuristics:
   - Hierarchical:
     - single linkage, average linkage, complete linkage, density seeking, more than two methods
   - Nonhierarchical:
   - Array based:
     - rank order clustering, direct clustering, bond energy, cluster identification, occupancy value
   - Assignment mode:
   - Others:
     - linear programming, goal programming, graph partitioning, simulated annealing, fuzzy mathematics (c-mean), expert systems, neural networks
5. Decision variables:
   - Number of machines of a given type to be assigned to a given cell
   - Number of parts or machines assigned to any given cell
   - Number of operations or tool copies per part per group
   - Batch size
6. Objectives:
   - Minimize intercellular travels
   - Minimize intracellular travels
   - Minimize setup time or maximize machine scheduling flexibility
   - Maximize similarity (or minimize dissimilarity) or compatibility measure
   - Minimize total production cost
   - Minimize exceptional elements cost (subcontracting, duplication, or both)
   - Minimize machine idle time
   - Maximize machine utilization
7. Constraints:
   - Number of groups (cells or part families)
   - Number of parts per group
   - Number of machines per group
   - Machine capacity
   - Each part machine or both belongs to one part family or machine group
   - Annual operating budget
   - Tool or processing requirement of parts

Figure 3.3 Model Characteristics of Cell Formation Procedures

3.2.1 Comparative Studies of Cell Formation Techniques

Recently, some studies have been undertaken to compare the performance of different part-machine grouping algorithms. Shafer and Meredith (1990) report problems with procedures based on machine grouping followed by part assignment because the machine grouping procedures placed all the machines of one type into a single group. This contrasts with procedures that group parts first, where the secondary machine assignment process can split multiples of machine types across different groups. Simultaneous part-machine grouping procedures were found to have difficulty identifying groups, because they tended to merge groups even if there was only a small overlap between them.

Miltenburg and Zhang (1991) found the Ideal Seed Non-Hierarchical Clustering Algorithm (Chandrasekharan and Rajagopalan 1986) to be slightly superior at grouping (achieving a high usage of machines within the cell and few parts requiring processing in more than one cell) their randomly generated data sets, but generally found little difference between the nine algorithms they tested. Some algorithms did however tend to produce a few large cells, while others tended to produce a larger number of small cells (where each machine is visited by most parts in the cell) and one large cell for the parts that do not fit in the small cells. They also report that where a well structured solution exists to a given problem, all of the algorithms will find it most of the time.

Kandiller (1994) assesses the inter-cell movement and cell density, work load balance, and cost of machine under-utilisation, achieved by six algorithms with a variety of data sets. All the algorithms were found to have their particular strengths and weaknesses making them more or less appropriate depending on the specific problem to be tackled. The Zodiac algorithm, developed from the Ideal Seed Non-Hierarchical Clustering Algorithm, (Chandrasekharan and Rajagopalan 1987), gave the best all round performance.

This research draws attention to the fact that several part-machine grouping algorithms struggle to fulfil their primary function of cell formation. The problem of how to compare the quality of solutions is also raised. For example, an understanding is required of how the pattern of the block diagonal relates to performance objectives. Decisions taken to refine the part machine grouping are at least as significant determinants of performance as the initial rough solution produced by clustering algorithms. Moreover, performance is determined by other elements of the manufacturing system, such as management and control subsystems. Different part-machine grouping solutions may be the most desirable depending on their combination with different subsystem designs.

3.2.2 Strategic Implications of Part-Machine Grouping

A few authors have proposed that cell formation decisions should be taken in a strategic context. Vakharia (1986) for example, argued that "cell formation should not be based on any one objective; rather it should be a decision based on several objectives which are usually conflicting, and thus have to be prioritized. Also some of these objectives are based on corporate policies, such as the degree of flexibility required to maintain a certain market share. This leads to the decision of cell formation being based on strategic as well as operational policies." (p. 259). He identifies five manufacturing systems with different degrees of cell independence: 1. All cells complete all the parts they make; 2. Some cells share a common piece of equipment; 3. Part families can be processed in more than one cell; 4. Serial cells, where the output of one cell is the input of the next cell; 5. jumbled flow job shop. The effects of each cell type on strategic (process flexibility, product customisation, additional capital investment requirements) and operational (set-up times and costs, types of equipment required, inter and intra-cell scheduling requirements, throughput rate, and machine utilisation) variables is then hypothesised. He does not however, indicate how specific cell types can be deliberately created, and does not address the relationship between strategic and operational performance.

Yang and Deane (1994) support Vakharia's argument that cell design decisions must be viewed as multi-criteria decision making problems that include strategic criteria. They investigate the performance implications of part set-up time similarity, process-time similarity, and cell size, using a queuing model. These are then related to strategic competitive priorities such as, throughput time, flexibility, cost, delivery reliability, and new product introduction. Specifically, they determine that as part set-up time and part processing-time similarity increases, set-up time, throughput time, the variance between throughput times, and the batch size that minimises cell flow times decrease. Increasing cell size is generally expected to increase the variation in set-up and processing time requirements. Their hypotheses for the strategic impact of choices between few large cells and many small cells are summarised in Figure 3.4.

They suggest two alternatives for introducing part set-up time similarity and processing time similarity considerations into the cell formation analysis. One approach would be to incorporate these criteria into the traditional cluster analysis models. The other option would be to fine-tune the results of part-machine grouping solutions produced by normal methods according to these criteria. More generally they advise that the choice between routing-oriented and part-oriented approaches to cell formation should be based upon whether opportunities for set-up reductions are expected from new technology or through incremental industrial engineering improvements respectively.

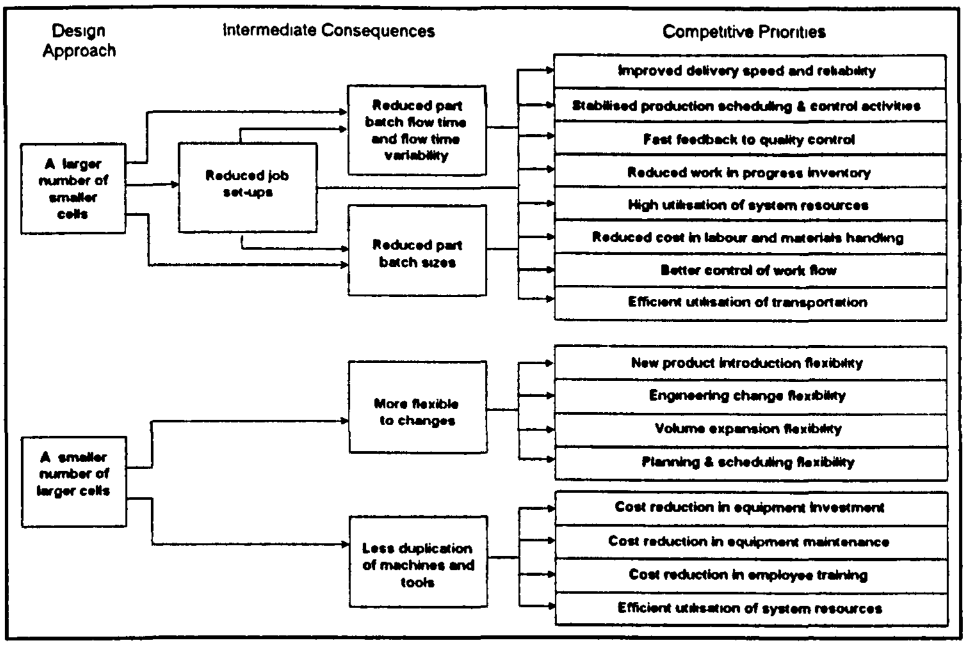


Figure 3.4 Strategic Impact of Cell Size (Source: Yang & Deane 1994)

This work links cell design parameters to operational and strategic performance. Cell design parameters are also related to cell design methods. However, the scope of the work is limited and relationships between operational and strategic performance are hypothetical. Incorporating set-up time similarities into traditional cluster analysis models would be difficult because set-up times for individual operations within a cell will be affected by the composition of its product family and the sequence in which they are produced.

Sheu (1994) sees cellular manufacturing as an extension of the focused factory concept (Skinner 1974), where the primary objective of cell design is to support the strategic objectives formulated at the focused unit level. The problem of designing focused manufacturing units is presented as one of assigning products and resources where the primary trade-off in the design process is between achieving a high degree of focus (ie. similar competitive priorities) within each unit and minimizing the resources required.

With regard to methods for designing focused manufacturing systems, Sheu reports that there are few available, and none consider capacity constraints. A heuristic based on a composite similarity index, that recognises both manufacturing tasks and resource requirements, is presented for generating solutions with different emphasis on these two objectives. Two measures are defined to evaluate the solutions for degree of focus and average resource similarity. Cellular manufacturing can then be applied within each focused unit. This work highlights the importance of clustering products with similar competitive priorities. Beyond this however, the means to create the desired competitive performance is not addressed.

3.2.3 Limitations of Part-Machine Grouping Research

There are many issues involved in the problem of part-machine grouping. The main concern this research has with part-machine grouping, is how useful is this body of knowledge and tools in providing companies with practical assistance to design better cellular manufacturing systems. Key issues are discussed below.

Practical Application

Burbidge (1989) points out that the majority of part-machine grouping procedures only concern themselves with the formation of groups within a department, and give no guidance on how to partition the material flow between cells, at a company or factory level, or within cells. He suggests that, because many part-machine grouping procedures do not account for the possibility of performing certain operations on more than one type of machine, they will have difficulty in achieving an effective solution to an industrial problem. Another common hindrance to solving practical problems he notes, is to treat all machines equally in the grouping analysis. Instead, he advises that clustering takes place initially around those machines from which work can not be readily transferred, and which the company only has one of. Processes required by most parts and equipment that can easily be distributed between cells are ignored until the cells are formed. Production Flow Analysis (PFA) is advocated as a method that does not have these deficiencies. Burbidge (1994) states, that only PFA can claim to have been used in at least thirty six cases to find a total division of a manufacturing system into groups that complete the parts they make.

Srinivasan and Navendran (1991) report that most algorithms are able to deal with well structured data sets but fail to provide acceptable results when applied to ill structured matrices. Offodile, Mehrez and Grznar (1994) contend that practical machine-part grouping problems do not lend themselves to partitioning into mutually separable clusters. Therefore, they suggest that a good algorithm should be able to find the natural clusters present in a data set and separate them from the exceptional elements. Thereafter the concern should be with analysing the cost-benefit trade-off between machine duplication, subcontracting, and intercellular movement.

Many part-machine grouping procedures require the number of parts and machines to be specified as part of the problem. Burbidge (1982, 1994) argues that group size should be determined as a result of the analysis rather than be specified as a precondition. Srinivasan and Navendran (1991) suggest that to pre-specify group size contradicts the fundamental philosophy of GT: that groups exist naturally.

Wemmerlöv and Hyer (1986) emphasize that cell formation is a complex and practical problem. They conclude that "designing manufacturing cells is an iterative and multi-objective process that can be supported by formal techniques but that also requires human decision makers with extensive knowledge of and experience with the company's products and manufacturing processes." (p.145). Vakharia (1986) reports that authors of "descriptive" (methods that do not rely on mechanical operation of an algorithm) approaches to cell formation stress the importance of local factors that are not easily identified. The fact that such factors are not readily considered with "analytical" approaches would seem to decrease the ability of those approaches to successfully tackle practical problems.

Research Objectives

Brandon and Schäfer (1992) note that the majority of cell formation approaches do not address the actual problems encountered in the design of Group Technology systems, concerning themselves more with the development of faster algorithms rather than producing better cellular manufacturing systems. Kusiac and Cheng (1991) find that current research into mathematical programming approaches to part-machine grouping concentrates more on modelling the problem than on developing effective solution algorithms.

System Focus

Part-machine grouping is only one part of the problem of designing a cellular manufacturing system. Wemmerlöv and Hyer (1986) indicate that, "Designing cellular manufacturing systems is a complex undertaking with broad implications for the organization. It involves the manufacturing system as well as related support systems." (p. 126). They do suggest that structure decisions will tend to precede operation decisions in the design process, and that part-machine grouping is important because it effects most subsequent decisions. However, they also indicate that system performance is a function of both structure and operation, and while they might be conceived and judged independently they must also be considered together. Brandon and Schäfer (1992) point out that "the most celebrated implementations of Group Technology share a holistic commitment to the cellular approach . . . Unfortunately, an alarming neglect of the holistic approach is evident in many modern contributions to GT." (p. 189)

3.3 Methodologies for Designing Cellular Manufacturing Systems

This section reviews methodologies for designing production systems that are relevant to cellular manufacturing. By considering cellular manufacturing within the context of the total production system, a broader view of the systems changes necessary to enable and exploit a cellular structure is achieved.

3.3.1 Simple Industrial Engineering Methods

There are a few approaches to the design of cellular manufacturing systems that consider cellular manufacturing to affect the whole manufacturing system but on the whole are characterised by a rigid view of what features should comprise a cellular manufacturing system, and have very clear ideas about how they should be applied. There is also a tendency for such methods to assume a fixed order for the design and implementation of their cellular manufacturing features. These are referred to here as simple industrial engineering methods to distinguish them from those based on systems engineering which are described later in section 3.3.4. Typical examples of this type of method are Burbidge (1994), Black (1991) and Nyman (1992).

Burbidge's approach, refers to the introduction of group technology, but as explained in Chapter 2, his approach to group technology is compatible with the concept of cellular manufacturing. His strategy has been developed through his extensive involvement in implementing cells in industry (Burbidge 1992). Burbidge suggests that the only way to simplify a change of this complexity, is to divide it into a series of independent projects, each of which is exactly specified to describe the nature of the change, the method to be used, the outputs required, the timing of the project and the condition when the project is deemed to be complete. He identifies this set of projects, though reference to his other writings on the subject would be necessary to obtain any detail about the nature of the changes or the methods to be used. He does however, supply eleven principles for simplifying the design of cellular manufacturing systems. Most of these are concerned with part machine grouping.

1. Form cells
2. Reduce set up times (using SMED)
3. Integrate quality control
4. Integrate preventative maintenance
5. Level and balance
6. Link cells - Kanban
7. Reduce WIP
8. Build vendor programmes

Figure 3.5 8 Steps to Integrated Manufacturing Production Systems using Linked Cells (Black 1991)

Black (1991) presents an eight step process for achieving what he calls integrated manufacturing production systems using linked cells. His concept of linked cells provides a very specific format for the design of the material flow system to conform to. Black treats the design of each feature as separate issues but provides no advice on how to approach project management of the overall process. The desire to design a cellular manufacturing system is assumed at the start of the process and the issues of design evaluation and justification are not dealt with.

Ingersoll's approach as presented by Nyman (1992) is slightly less prescriptive than the other two methods described here, and although it makes no explicit reference to systems theory it exhibits many of the features of the manufacturing systems engineering approaches described in section 3.3.4. There are three broad steps to the design process, macro facility planning, conceptual cell design, detailed cell design, though other activities such as project management, justifying cellular manufacturing and selling the concept to management, implementation, auditing cell performance and automating cells are also described. The main features that set this design process apart from the others in this section are the more loosely defined cellular manufacturing features, and also the progressive development from low resolution system wide design to high resolution design of specific features.

3.3.2 Just-in-Time (JIT) Based Methodologies

JIT is a broad based approach for the organisation of manufacturing that was developed in conjunction with a cellular organisation (Ohno 1988). Cellular manufacturing and JIT are closely related and are often partnered together (Ramarapu, Mehra and Frolick 1995; Wemmerlöv and Hyer 1989). However, the principles and objectives associated with the design of JIT manufacturing systems are more focused on the operation and performance of the production system than is the case with cellular manufacturing.

JIT is commonly viewed as a philosophy of continuous waste elimination. Transportation of materials, motion of workers, overproduction, inventory, waiting time, production of defective goods and over-processing are all identified as sources of waste (Ohno 1988). Many tools and techniques have been identified or developed to tackle various aspects of waste elimination, such as kanban, single minute exchange of dies, Poka-yoke, and layout improvement (Shingo 1989). Cellular manufacturing as described in Chapter 2 can be seen to incorporate, or at least support the application of many of these.

The introduction of JIT does not appear to be treated as a process of design followed by implementation. Instead JIT systems evolve towards the JIT ideals by incremental application of tools and techniques identified to eliminate waste. Many of the processes available for guiding the implementation of JIT are similar to those described in section 3.3.1 for designing cellular manufacturing systems. A set of JIT tools and techniques are defined to be applied individually in a given sequence, for example Shingo (1989) describes the development of JIT at Toyota, and O'Grady (1988) presents a five stage framework based on his observations of JIT implementations. A more flexible approach has been suggested by Bicheno (1994). He proposes a two stage process, identifying a set of JIT tools and techniques for each stage. The first stage comprises those tools and techniques that are either relatively easy to implement or provide a foundation for stage two tools and techniques. Stage two is generally considered to be a more advanced form of JIT, with more streamlined, synchronised material flows, some elements of which may only be suitable for high volume, low variety environments. He does not however suggest how the tools and techniques should be selected from within each stage, and the relationships between the various tools and techniques is not clear.

World class manufacturing (WCM) is a closely related production philosophy that embraces cellular manufacturing and JIT. The distinguishing characteristic of WCM is its emphasis on identifying and serving customer requirements and the importance it assigns to the role of humans in the system. Simple material and information flows assume additional significance for WCM as they support empowerment and team working, which facilitates learning and continuous improvement, and increases flexibility. WCM as defined by Schonberger (1986) and Hayes Wheelwright and Clark (1988) is an unstructured incremental approach to JIT, in terms of the introduction of JIT tools and techniques, the progressive refinement of their application and the way JIT is spread through the factory. The design process therefore amounts to a set of actions to initiate the change, putting appropriate structures in place or removing barriers such that objectives and performance are obvious, and involvement in systems improvement encouraged and facilitated.

As a component of JIT the cellular manufacturing concept is reduced to the use of a cellular organisation, and often more narrowly referred to as layout improvement. Cell formation is not addressed in detail in the JIT/WCM literature. Some authors, such as Hutchins (1988), barely discuss the subject; others, such as Monden (1983) restrict their discussion to what should be achieved without describing how. Some authors reference cell formation techniques in cellular manufacturing / group technology literature: see for example, Harrison (1992) and Kelleher (1986). Where cell formation is tackled it is generally considered to be a straightforward issue. Cells are simply identified and implemented one at a time, by grouping the machines necessary to produce a chosen group of similar products: see for example, Arogyaswamy and Simmons (1991), Hay (1988), and Schonberger (1986). Over time, a policy of investing in multiple small machines rather than large machines is expected to eliminate the problem of not having enough machines to place in each cell.

3.3.3 Socio-Technical Systems Analysis and Design

Although the design of a cellular manufacturing system would not be the explicit objective of a socio-technical system design exercise, its historical association with cellular manufacturing and the frequency with the solution will incorporate autonomous group working warrants that socio-technical system design is reviewed alongside other methods for designing cellular manufacturing systems. The socio-technical systems approach introduced systems theory to production engineering and organisation design, and introduced the notion of integrating the organisation of both technology and workers.

There is no definitive method for designing a socio-technical system, although Hill's (1971) process for socio-technical system design, based on his work with Shell UK, is widely known. However, Klein (1994) draws attention to the fact that it was developed for a specific application and when used out of context, there are many interdependencies between the technical and social systems that do not come to light using this method. Hill's process is summarised in Appendix C. Purists argue that the lack of procedure and design rules are an essential component of the open systems approach upon which socio-technical design is based (Klein 1994; Neumann 1990). Instead a set of general principles are advocated (Cherns 1976, 1987): see Figure 3.6. These principles should be interpreted for a given situation through open-ended grounded diagnosis and action formulation.

i. *Compatibility*. The way design is done should be compatible with the design's objectives. Design should be as participative as is practical and recognise the inevitability of conflict. Members must reveal their assumptions and reach decision by consensus. Joint optimisation does not mean modification of the technical system for social reasons but taking each decision on both technical and social reasons.

ii. *Minimal critical specification*. No more should be specified than absolutely essential. What is essential should be identified. This principle implies the minimal critical specification of tasks, the minimal critical allocation of tasks to jobs or of jobs to roles and the specification of objectives with minimal critical specification of methods of obtaining them.

iii. *Variance control*. Variances (deviations from standard in the production process) should not be exported across organisational boundaries.

iv. *Boundary location*. Boundaries should not be drawn so as to impede the sharing of information, knowledge and learning.

v. *Information flow*. Information for action should be directed first to those whose task it is to act. Information for record should readily available for call only when and as needed.

vi. *Power and authority*. Those who need equipment, materials, or other resources to carry out responsibilities should have access to them and authority to command them. In return they accept responsibility for them, and for their prudent and economical use.

vii. *The multifunctional principle*. Organisations need to adapt to their environments. This should be achieved through training and development to enlarge the response repertoires of individuals and teams rather than through hiring experts as these complicate the lines of command or allocations of responsibility within the organisation.

viii. *Support congruence*. Support systems should be designed to reinforce the desired performance of the designed organisation. Cherns suggests that according to the second principle, it is preferable to design support from scratch to create an ideal organisation, which can be later be constrained according to practical or policy considerations, rather than to attempt to modify existing support systems for compatibility with the new organisation.

ix. *Transitional organisation*. There is a period of transition to achieve the new organisation that requires planning and design. The transitional organisation is both different and more complex than either an existing or the new one. The design team and its process are a vehicle of transition. Start up and debugging should be planned and designed to enhance training.

x. *Incompletion*. As soon as a design is implemented, it will have consequences that create the need for redesign. Implementation begins with the start of design and with implementation comes evaluation. The multifunctional principle indicates the way to address this. Redesign is not the task of a special design team; it is the function of self-regulating operating teams provided with the techniques of analysis, the appropriate criteria, and the principles of design.

Figure 3.6 Principles of socio-technical systems design (Source: adapted from Cherns 1987)

Socio-technical design has a strong basis in practical application, and a track record of successful projects. The explicit theoretical foundation and the design principles derived from this do not impose prescriptive solutions. This provides a wide range of applicability and does not suggest a ceiling to continuous improvement. The systemic values of socio-technical systems theory make several important contributions to our understanding of the design process, concerning the need to integrate the design of the technical and social subsystems of the production process, and to integrate design and implementation. The latter also leads to the notion of a circular process without beginning or end. The need to reflect desired operating principles in the design process is also a valuable insight.

Despite empirical success, there are arguments to suggest that while the features typically associated with a socio-technical system may be valuable, the theoretical explanations for their benefits may be misguided. For example, Kelly (1982), points out that while socio-technical systems theory claims joint optimisation of the technical and social systems, in the majority of cases of socio-technical design the technical system has not been altered. Instead they have been prompted by technical innovations that have failed to deliver expected benefits, and have adapted the social system to the technology to yield higher productivity.

With regard to job design, Kelly questions the correlation between changes in intrinsic motivation, job performance and job attitudes. He draws attention to the acquiescence of autonomy to managements economic needs in published cases of socio-technical redesign, and argues that the productivity improvements resulting from the use of autonomous work groups are primarily based on flexible work assignment, which allows the levelling of any uneven work loads that exist across the production system. This has enabled the same amount of work with less people, or where there was spare capacity in the technical system, increased output with the same number of people. He argues that the changes in pay levels and to the payment system accompanying many implementations of autonomous work groups, are likely to have been important in securing higher rates of working or agreements for job losses. The connection between improved quality and quality linked payment systems is also noted.

Buchanan (1979) highlights the fact that the socio-technical systems analysis does not deal with the impact of changing the primary production unit's work organisation on management and auxiliary systems. In addition, he suggests that the analysis is dependent on the ingenuity of the designer, stimulating the generation of job design hypotheses rather than generating them directly from the analysis.

3.3.4 Manufacturing Systems Engineering Methodologies

Increasing recognition of the integrated nature of manufacturing systems has led to a broader interest in systems theory, and systems engineering in particular, as a framework for understanding and designing production organisations. As a result, manufacturing systems engineering (MSE) has emerged as a new discipline (Hitomi 1990). The MSE approach recognises the relationships between the various components of the production system and attempts to ensure that they are all compatible and aligned with a company's manufacturing strategy. Three MSE methodologies, Lucas, Wu, and Drama, are reviewed below.

The Lucas Methodology for Manufacturing Systems Redesign

The Lucas methodology, described by Dale and Johnson (1986), Dale and Fielden (1988), and Parnaby (1986), is a proprietary methodology, developed by Lucas Engineering and Systems (LE&S), from their experience at overhauling manufacturing operations throughout Lucas Industries PLC since the early eighties. Its purpose is to restructure a traditional (functionally organised) manufacturing system into cells and to introduce JIT and TQM methods of operation. The design process was rationalised to allow rapid replication of the benefits across the business. It has been widely and successfully used by LE&S to redesign over six hundred businesses, approximately half of which are outside of the Lucas company. Case examples report significant performance improvements such as reduced lead times and stock holdings (Dale and Fielden 1988; Dale and Johnson 1986; Kellock 1992).

There is little material available in the public domain describing the methodology, and what is available does not give a consistent presentation of the approach. This is perhaps inevitable with a practical consulting tool, which does not need to provide a rigorous model, and is likely to be amended frequently to suit the job in hand. The author supplemented the literature by interviewing LE&S consultants to enhance his understanding of the methodology.

Figure 3.7 presents a typical example of a flow chart describing the Lucas methodology. The process steps are described in more detail in Appendix C. Redesign projects are typically broken down into blocks of work of approximately six months duration for a project team of 7-8 people (some of which will be only part time). The reason being that experience has shown that momentum begins to diminish beyond this time.

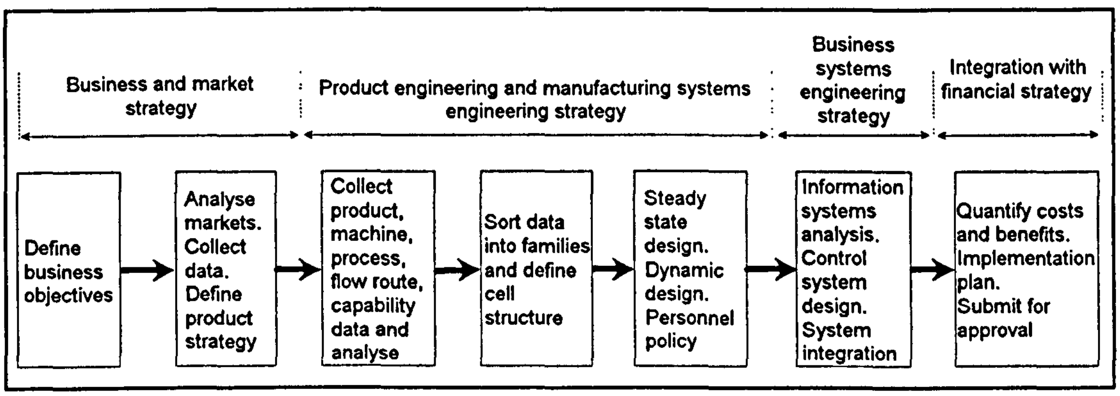


Figure 3.7 Flow Chart of Lucas Methodology (Parnaby 1986)

This methodology assumes that cellular manufacturing is generally a better way of working and that the change will be desirable if it can be cost justified. The design task is simplified in practice, by restricting the choice of procedures to be used for part-machine grouping, the range of solutions considered for issues such as production control. However, the lack of detail and decision support available suggests that facilitation by an experienced consultant would be necessary to ensure good results.

The defined process is top-down and sequential. While strategic objectives and constraints are made explicit early in the process, to provide guidance for remaining design decisions, objectives are set before analysing the market requirements and company capabilities, thereby raising the possibility that inappropriate or unobtainable objectives may be set.

There is also no explicit mechanism for translating corporate objectives and market requirements into manufacturing system design and performance measures. Consequently no clear framework is constructed for evaluating the design throughout the process. In practice, these problems may be resolved by the experience and knowledge of managers setting the objectives, and of the consultants operating the design process.

Lewis and Love (1993) argue that, in breaking down the design of the manufacturing system into discrete steps, the methodology ignores important interrelationships within the system, and that relationships and their effect on performance are only evaluated at the end of the design process. For example, work design and control system design after the physical restructuring. This suggests that the intention is to make these elements fit the chosen structure, rather than recognising the impact of work design and control system on manufacturing performance and accounting for their requirements when designing the manufacturing architecture. Even dynamic design is shown to take place before the control system has been designed. Use of multidisciplinary task forces as discussed by Parnaby (1986) may help integrate these design stages and ensuring compatibility at the interfaces of the production system.

Wu's Methodology for Design and Evaluation of Manufacturing Systems

Wu's (1992) methodology is based on the general problem solving cycle of systems engineering theory. It has been developed as a general framework for analysing and designing manufacturing systems as shown in Figure 3.8. The process stages are elaborated in Appendix C. The process addresses recognition of the need for change and redesign of the physical and control systems, to rectify poor performance or to pursue new objectives or opportunities. The methodology, uses narratives, input/output diagrams, flow charts, and problem solving techniques. Simplicity and focus are offered as general principles to guide the design.

Rigorous practical evaluation of the methodology has not been undertaken, though it has been widely used during industrial projects by undergraduates and postgraduates at Brunel

University. Wu claims that feedback from these projects is generally favourable.

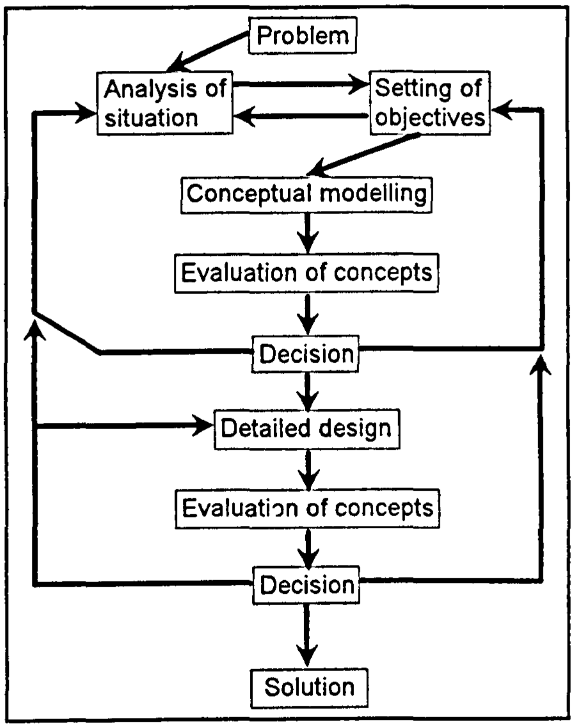


Figure 3.8 Structure of Design & Evaluation Methodology (Wu 1992)

The methodology is not exclusively for planning the change to cellular manufacturing. Its problem solving cycle of systems engineering can be used to continuously appraise and improvement the manufacturing system (whether it is already cellular or not). However, a cellular organisation is advocated.

Top-down objective setting is balanced by bottom up appraisal of the existing manufacturing system in order to build on existing strengths and ensure that realistic objectives are set, without restricting creativity for the design of the new system. This approach diminishes the criticism that systems approaches are overly problem oriented and neglect wider influences on design such as strategic opportunity. The need for a framework for evaluating the design throughout the process is made explicit.

A systemic perspective is facilitated by splitting the design process into two stages: conceptual and detailed design. By reducing the level of detail considered at a conceptual level the designer can consider more components of the manufacturing system and their interactions. A significant level of detail is pursued in detailed design, including machine selection and data structures for information systems. Structured methods of analysis and design such as $IDEF_0$ are utilised, which incorporate a disciplined approach to documentation.

Design of the social system is neglected. Although the human resources are included in the situation analysis, such issues as job design, incentive systems and training do not feature explicitly in the design components of the methodology. The design of structures for continuous improvement of the manufacturing system is not incorporated either.

Decision Rules for Analysing Manufacturing Activities: The DRAMA Methodology

The DRAMA methodology was initially developed by Bennett and Forrester (1993) from ICL's experience in designing and implementing market focused, modular, production systems at their Ashton plant for the design and assembly of mainframe computers. The methodology's general applicability was then tested against thirteen cases covering electromechanical, mechanical engineering and the textile industry. However, no deliberate and explicit use of the methodology has been reported.

The methodology provides a framework of enquiry that links strategic analysis to the design of a manufacturing system using narratives, flow charts and decision trees. DRAMA views MSD as a decision process, though drawing on systems theory, this arranged in a hierarchical and modular structure. The design process is partitioned into ten distinct components that represent decisions at the strategic, tactical, and operational levels of the business, as shown in Figure 3.9. This structure is intended to allow the designer to select only those elements that are of immediate interest. It is suggested that the components of DRAMA can each be viewed as a set of gears, all continually turning, sometimes at different rates but always subject to change from the other gears. In general, the methodology progresses from

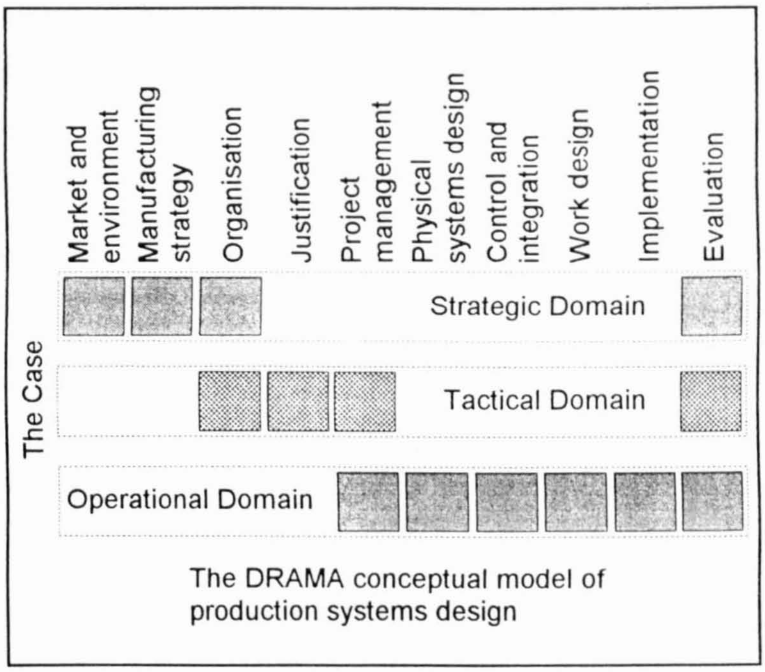


Figure 3.9 The DRAMA Conceptual Model of Production Systems Design (Bennett and Forrester 1993)

the strategic domain to the operational domain and exhibits a sequential progression through the components within each domain, though it does recognise that there are many interconnections between components and that iteration will be necessary. The process stages of DRAMA are described in more detail in Appendix C.

DRAMA is not specifically for designing cellular manufacturing systems though it is committed to the principles of achieving market focus and recognises a cellular organisation as being an appropriate solution. The market focus also manifests itself in a top-down approach to analysis and design. DRAMA takes a broad and comprehensive view of the manufacturing system and the design process. Different levels of organisational decision making within the company are made explicit helping to bridge the gap that currently exists between manufacturing strategy and its translation into an operational design. Evaluation is shown to take place at each level of the organisation and within each module of the process. Evaluation also includes self assessment of the design process.

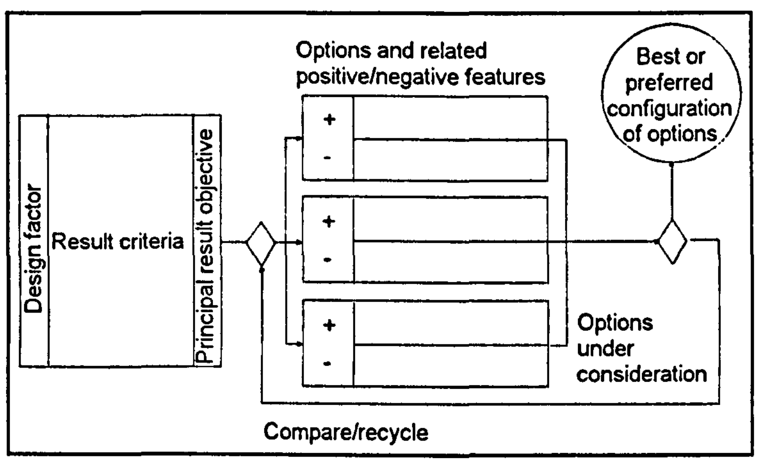


Figure 3.10 Format of a Design Option Guide (Bennett and Forrester 1993)

At each stage in the methodology, "Key Parameters" that influence the design are identified as prerequisite areas of analysis or audit. These may come from the environment or may be found in an earlier stage in the methodology. The decision process is presented as a flow chart with the key parameters as inputs. Decision support is provided by one or more Design Option Guides (DOG), see Figure 3.10. The DOG requires designers to make explicit, priorities among the results that can be affected by each decision. The designer is then invited to select from a range of decision options based on the direction of their expected impact on the desired results. The framework of the DOGs is considered to be more important than the detail. In discussion, Forrester said that he would recommend companies to construct their own DOGs.

Use of DRAMA does not appear to result in a detailed design specification that could be implemented directly. Even for many design decisions in the operational domain the DOGs appear to work at conceptual level, helping the designers to settle such issues as what type of layout should be adopted and whether to centralise or distribute tool storage. DRAMA does not for example, deal with the identification of capacity requirements or the balancing of capacities between processing stages.

A key feature of the DRAMA is that it advocates concurrent design of the physical system, control and information system and work design is advocated. However, interrelationships between the Decision Option Guides for these systems are not readily addressed apart from assuming a multifunctional design team and recognising the need for iterative design cycles between the components.

3.4 Additional Insights into the Practice of Designing Cellular Manufacturing Systems

With the exception of many part machine grouping tools, most of the methods reviewed above reflect the practice of designing cellular manufacturing to a certain extent. However, there is very little literature concerning the use and performance of these methods. Case studies tend to emphasise the cell features implemented and the overall performance benefits rather than describe the way design decisions were taken and the reasons that have resulting in the specific outcomes of decisions.

Further insight into the cell design process has been obtained through interviews and discussions with industrialists and consultants who have designed and introduced cellular manufacturing systems, and through project work concerned with the design of cellular manufacturing systems (Nimmons 1992, 1994; Nimmons, Williams & Cursham 1995).

Mission and Process Performance

Nyman (1992) argues that in order to ensure that cells are applied in the most profitable manner, it is important to understand the connection between manufacturing and marketing strategies. Unfortunately he observes that in practice, the decision to install cells is usually made by manufacturing people for operational reasons, and that their connection to anything higher than plant goals is usually obscure.

Of the cases encountered, the most successful were characterised by design processes that developed clear performance objectives and an explicit understanding of how cellular manufacturing will address these objectives. This is perhaps best illustrated by a case of the reverse (Nimmons 1992), where they took advantage of their need to move out of their existing facility, to adopt a cellular layout in the new building. As they did not have any specific objectives to address through cellular manufacturing, they made little attempt to exploit their new organisation and a year later they were still puzzled as to why they had not improved performance.

Fritz, Schmid and Wu's survey of manufacturing systems design revealed that only a small proportion of companies use formal methodologies for designing their manufacturing systems. The authors criticize available methodologies for being too impractical, too complex, too general, too abstract, and for being too narrow in focus (both in the number of stages in the design process being supported, and the number of manufacturing system elements considered).

Scope of Design Process

Several implementations were hindered by the designers not taking a broad enough view of the systems changes required to introduce cellular manufacturing. The case described above took a very limited view of cellular manufacturing and got similarly limited results. In a second case, a cellular structure was implemented rapidly with little consideration of the wider system. Although some benefits were obtained, their performance was significantly improved at a later stage using the principles and techniques of JIT to exploit the potential of the cells (Hallihan, Williams & Sackett 1995). This observation coincides with the views of researchers cited earlier in section 1.6

Design Stages

All of the consultants interviewed describe a preliminary business review phase to the design process in which performance is benchmarked, business objectives are defined, and pareto problems are identified. This stage allows them to use their experience to identify those issues whose resolution is most critical to achieving the desired performance improvements and potential solutions to the problems. In two cases of the introduction of cellular manufacturing reviewed where a consultant was not employed, the members of the company responsible for the introduction of cellular manufacturing determined "*best practice methods*" through available literature, and study visits for example, through the DTI Inside UK Enterprise Initiative, and then selected those that were suitable for their company requirements. However, development of a concept design appears to be problematical. In a survey of cellular manufacturing in the furniture industry, Mugwindiri, Groves & Kay (1994) identify the lack of understanding of cellular manufacturing concepts as a common problem that hindered implementation. In a survey of manufacturing systems design, Fritz, Schmid and Wu (1994), identify the evaluation of design concepts as a major problem.

Design and implementation stages merge together, especially where pilots are used, as no sooner has implementation started than new understanding is generated which initiates refinement of the design. Evidence of this was displayed in a case that started with a poor design for part machine grouping, where the cell leaders renegotiated their cell contents among themselves as they began to appreciate the benefits of ownership.

Ramifications of Design Decisions

Two cases designed part machine groupings with unacceptable intercellular movements, because the significance of ownership on control of production was not appreciated. Decisions were therefore based on the cost of improving the organisation rather than the lost opportunity caused by a poor solution. Tradition and constraints of the existing system encouraged one case towards conservative decisions rather than looking for ways to eliminate the constraints. In both cases, the organisation has subsequently been improved. A cell leader in one case commented, that if they have any problems meeting the schedule now, it will more than likely involve the one remaining part they have that leaves the cell for an intermediate (electron beam welding) operation.

Similar difficulties arise in understanding the impact of elements of the wider production system on the performance of the cellular manufacturing system. In one case it was decided to retain a central cutter tool management system because it was new and had found to be beneficial in the existing functional organisation. Jobs were sent back to stores between each operation to be kitted for the next one. The cell's ability to control the flow of work between operations was lost, and with it, its ability to improve lead time and reduce WIP. Accountability was also diminished.

In a second case, the production planning and control system was reviewed as part of the change to cellular manufacturing. It was concluded that improved scheduling would help the cells reduce lead times and WIP and improve delivery, so a centralised OPT system was installed. This added another production control function and computer system between customer demand and production. The schedule was based on MRP data not the reality of the workable jobs in the cell, and the system was not responsive to the cells scheduling needs. It did not improve control of production. One of the cells in this case has since stopped using the OPT schedule as it has found that improving the organisation of the production process has reduced the scheduling problem and progress can be better managed using simple physical systems locally. However, a significant investment was made to implement OPT, and attention diverted that would have been better spent improving production methods and organisation. Moreover because other cells are still managed centrally, the opportunity to reduce the overhead of production planning and control has not been exercised.

3.5 Conclusions

This chapter has reviewed the theory and practice of designing cellular manufacturing systems. A range of approaches to this problem have been presented and their shortcomings have been discussed. Practical implications of the cell design process have been described.

The largest body of work found was concerned with developing procedures for part-machine grouping. These techniques perform the valuable function of defining in detail the organisation of parts and machines for cellular manufacturing. However, there are major shortcomings with these techniques, not least of which, is the fact that many can not adequately solve real industrial problems. Given the system wide features of cellular manufacturing described in Chapter 2, it is clear that, while the more practical part machine grouping techniques may find useful employment as part of a broader methodology, solving the part machine grouping problem will not be an adequate basis for the introduction of cellular manufacturing. Cell formation should also be guided by the way in which it expected that the new structure will enable performance improvements.

Some researchers have recognised the need for a broader approach to the design of cellular manufacturing and several methods have been developed to this end. Moreover, it is the author's experience that a broad perspective of the design task is associated with successful implementation of cellular manufacturing. The issues arising from reviewing these methods, that need to be taken into account to improve the process of designing a cellular manufacturing system are highlighted below.

- The design process must recognise the flexible nature of cellular manufacturing as defined in Chapter 2. This implies that the concept must be interpreted for a given situation before proceeding with detailed design and implementation of the various features. Simple production engineering methods have a fixed concept of cellular manufacturing embodied in their approach. Of the remaining approaches, only Wu's methodology makes explicit reference to concept design. However, DRAMA appears to operate primarily at a conceptual level.

- There is a need to make concept design explicit and to improve the support available. A significant hurdle to designing cellular manufacturing systems is the ill defined and flexible concept itself, and companies find conceptual thinking difficult. Neither of the methodologies that include concept design are exclusively for planning the introduction of cellular manufacturing, and consequently do not provide guidance in specifically developing a cellular manufacturing concept.

- A cellular manufacturing system should be designed to support the company's strategic objectives. The design process should help to understand the effect of design decisions upon performance. Due to the complexity of manufacturing systems, the relationship between the features of cellular manufacturing and performance will need to be determined for each specific situation. Of those methods that do recognise the influence of different objectives on the design, most rely on post design testing such as simulation to evaluate the quality of the design.

- The design process must address the full extent of the manufacturing system included in the cellular manufacturing concept. Most of the methods reviewed neglect some aspect of the manufacturing system.

- Most of the methods reviewed fail to account for the relationship between design and implementation.

- Current methods for designing cellular manufacturing systems do not adequately account for the complexity of production systems. Little consideration is given to the relationships between design decisions. For example, DRAMA does not help to determine the relative importance of system features identified in different decision domains, so effort can be focused on those that are critical to improving performance. The value of one decision option for supporting another in a different decision domain is also ignored. However, while it is desirable to account for this complexity, the method must remain practical and usable.

Chapter 4 Specification and Development of an Improved Process for Designing Cellular Manufacturing Systems

This Chapter brings together the conclusions of Chapter 2 and Chapter 3 in order to specify and develop an improved approach to the design of cellular manufacturing systems. The design task is defined in terms of the purpose of the design process, the extent of the manufacturing system addressed, and the process stages addressed. A process for generating a concept design for a cellular manufacturing system is developed.

4.1 Introduction

The analysis of the nature of cellular manufacturing in Chapter 2 has identified several characteristics that complicate the task of designing a cellular manufacturing system. In particular it is an ill defined and flexible concept, with complex indeterminant relationships between cellular manufacturing features and their effect on the manufacturing system. None the less, a valuable contribution is made by making these features and effects explicit. The review of existing methods for designing cellular manufacturing systems in Chapter 3 reveals that none are entirely adequate for tackling the complex task. Most of the processes reviewed did not address the full range of issues contained in the general model of cellular manufacturing developed in Chapter 2. None defined a procedure for tailoring a general model of cellular manufacturing to a specific situation. This chapter develops an improved approach to address these issues.

4.2 Purpose

The two extreme positions that can be adopted as the purpose of a manufacturing systems design process are embodied in prescriptive and design methodologies. Prescriptive approaches advocate the design and implementation of a fixed set of features often in a set sequence. Burbidge (1994) and Black (1991) have both presented methodologies of this type that focus specifically on the design of cellular manufacturing systems. Manufacturing systems design methodologies on the other hand tend to identify stages in the design process, the types of decision that should be being taken, and useful tools to assist the design, rather than specifying any particular features that the manufacturing system should possess. This does not mean that these methodologies are value free. Socio-technical systems theory for example, provides a set of principles to guide both the design process and the resultant manufacturing system. Wu (1992) and Bennett and Forrester (1993) also describe "best practice" approaches that might be incorporated into the design as appropriate. However, design methodologies typically stop short of supporting any particular design decisions or imposing any order for the design and introduction of elements of best practice. None of the design approaches reviewed in Chapter 3 were exclusively for designing cellular manufacturing systems and therefore cannot focus on the specific issues involved.

Advantages of prescription are speed of application and a well-defined end point to work towards. Disadvantages are the potential for wasted effort through implementing unnecessary features, or worse, reduced performance if they are inappropriate. Manufacturing systems design approaches should not suffer from these draw backs as the solutions proposed should be generated from analysis of the specific objectives and constraints of the company. Undertaking such an analysis and developing their own design ensures that a company understands why it is implementing the designed features, and will therefore be equipped to modify and improve the design in the future. Consequently designed systems are likely to be more robust than systems based on prescription. Unfortunately the strength of design methodologies is also their weakness. As they require the company to take more responsibility for the shape of the resulting manufacturing system design, they take longer, which can make it difficult for companies to sustain the necessary quantity and quality of design effort. Moreover, the necessary knowledge is not always available within the company, and old ways of working can confuse new thinking. This problem is emphasised with a change of the magnitude of introducing cellular manufacturing. More effort will also be required to communicate a common understanding of design objectives.

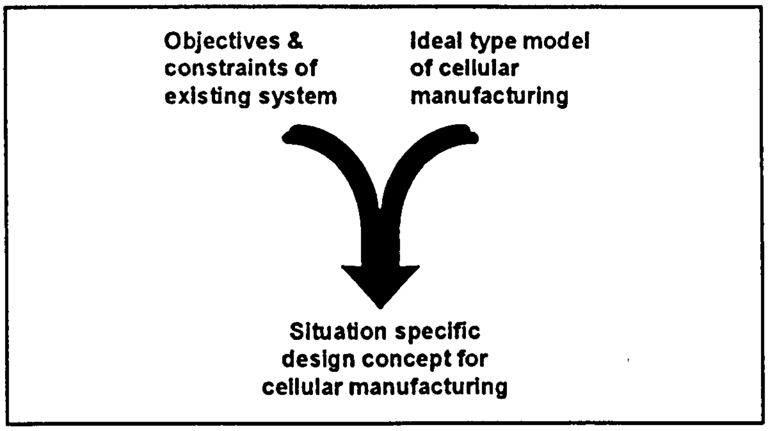


Figure 4.1 Tailoring an Ideal Model of Cellular Manufacturing

An improved approach would adopt the best features of each of these extreme positions. While prescriptive methods for designing cellular manufacturing systems can be criticised for their lack of consideration of the circumstances to which they are being applied, it is a waste to ignore existing knowledge and experience, that has identified the collection of compatible techniques and manufacturing system features that is recognised as the concept of cellular manufacturing. Rather than build up a situation specific version of cellular manufacturing from nothing, it would be possible to tailor an "ideal" model of cellular manufacturing, to suit the specific existing manufacturing system and its performance improvement priorities, as shown in Figure 4.1. Therefore, an improved approach would start from the position of having decided that cellular manufacturing is an appropriate way to organise production, and would have the specific purpose of defining how the general concept of cellular manufacturing (as defined and presented in Chapter 2, and embodied in the features and effects compiled in Appendix A) could be best applied to address the individual objectives and constraints of a given production system.

4.3 Scope of Cellular Manufacturing Systems Design

Most of the methods described in Chapter 3 focus on certain aspects of the manufacturing system and neglect others. This is understandable in the prescriptive approaches, which define the objectives in terms of the features they address. The systems methodologies however, should provide a framework within which all aspects of the manufacturing system can be designed.

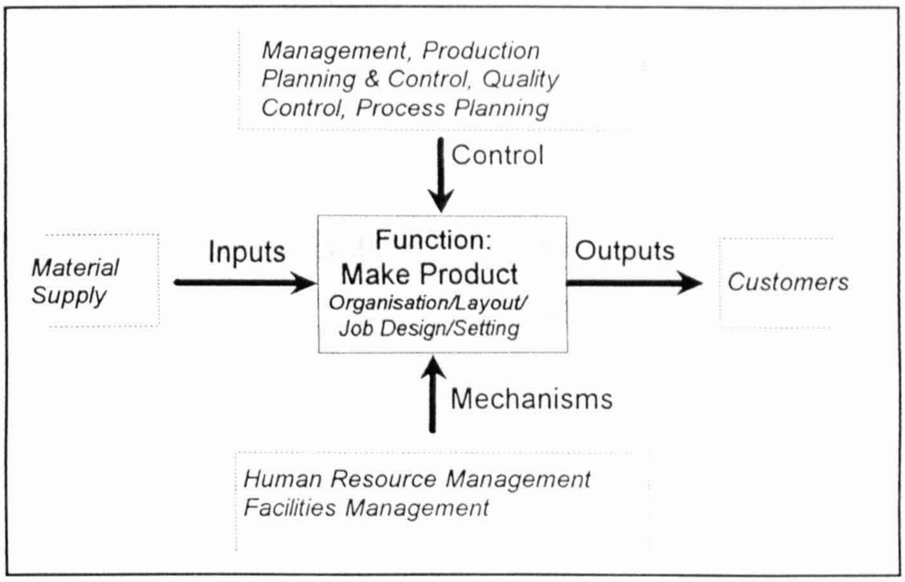


Figure 4.2 Scope of Cellular Manufacturing Systems Design

The model of cellular manufacturing features and their effects developed in Chapter 2 indicates that cellular manufacturing is a system wide concept. Figure 4.2 indicates the scope of the manufacturing concept using an IDEF0 representation of the manufacturing function. The concept of cellular manufacturing may be focused on the central function *make product* (eg. changing the organisation and layout of direct production resources, introducing flexible working and improving set-up procedures) but this organisation of the production function has implications for many supporting processes and systems. In particular, production planning and control must be modified to take advantage of the new organisation's ability to produce in small batches and coordinate the flow of work between machines. Quality control and stores procedures must be defined so that they do not interrupt the flow of material, and functions that supply and manage resources, such as personnel, training, production engineering and maintenance must make sure that their policies are aligned with the requirements of the *make product* function. For example, recruiting and developing multi-skilled operators, and choosing to purchase multiples of small machines, in preference to single super-machines. The arrows on the diagram represent four broad types of transaction with the production function: inputs, outputs, controls and resources. The design process must therefore define the organisation of the production function and the affected interfaces with supporting systems and processes. In practice, the scope of the design process is defined by the range of features associated with the cellular manufacturing concept, as compiled and presented in Chapter 2.

4.4 Process Stages and Procedure

The most clearly defined processes for designing cellular manufacturing systems described in Chapter 3 are those developed by Lucas and Wu based on the systems engineering problem solving process. All the consultants that were interviewed identified with a simple process, similar to systems engineering, comprising the following steps: analyse existing situation and set objectives, design system, and evaluate. However, the previous sections in this chapter have identified that an improved process would recognise the flexible generic concept of cellular manufacturing presented in Chapter 2 and would tailor this concept to address the specific objectives and constraints of a given production system. Such a concept can also evolve with the development of the theory and practice of cellular manufacturing. A concept design stage must be incorporated into the commonly accepted process for designing cellular manufacturing systems, where the general concept can be confirmed, updated and tailored to the current circumstances. While consultants indicated that they used their experience of cellular manufacturing to develop a vision of what features would be appropriate to a given company's specific production characteristics, performance objectives, and current performance inhibitors, only Wu's process makes explicit reference to concept design. Wu however, describes a general approach to functional modelling of the manufacturing system rather than the development of a cellular manufacturing concept.

The absence of a defined process for concept design allows this important activity to be neglected, and denies the means to do it from those without prior experience of designing cellular manufacturing systems. Therefore this section will develop a process for designing a cellular manufacturing system that incorporates a concept stage.

Systems engineering provides a system life cycle model which can structure decomposition of the design process. This identifies initiation, preliminary study, total system study, sub system studies, implementation, followed by stages concerned with realisation and utilisation of the system before returning to initiation. The problem solving cycle can be applied to all problems throughout this cycle, albeit with different emphasis at each stage (Buchel, Breuil and Doumeingts 1984). This can then be combined with a further decomposition of the design into concept and detail. The reduced detail considered when dealing with concepts allows a wider view of the manufacturing system. Therefore, concept design is applied to the total system and addresses strategic design objectives. The result of concept design provides more specific objectives and constraints to guide the detailed design of the sub systems.

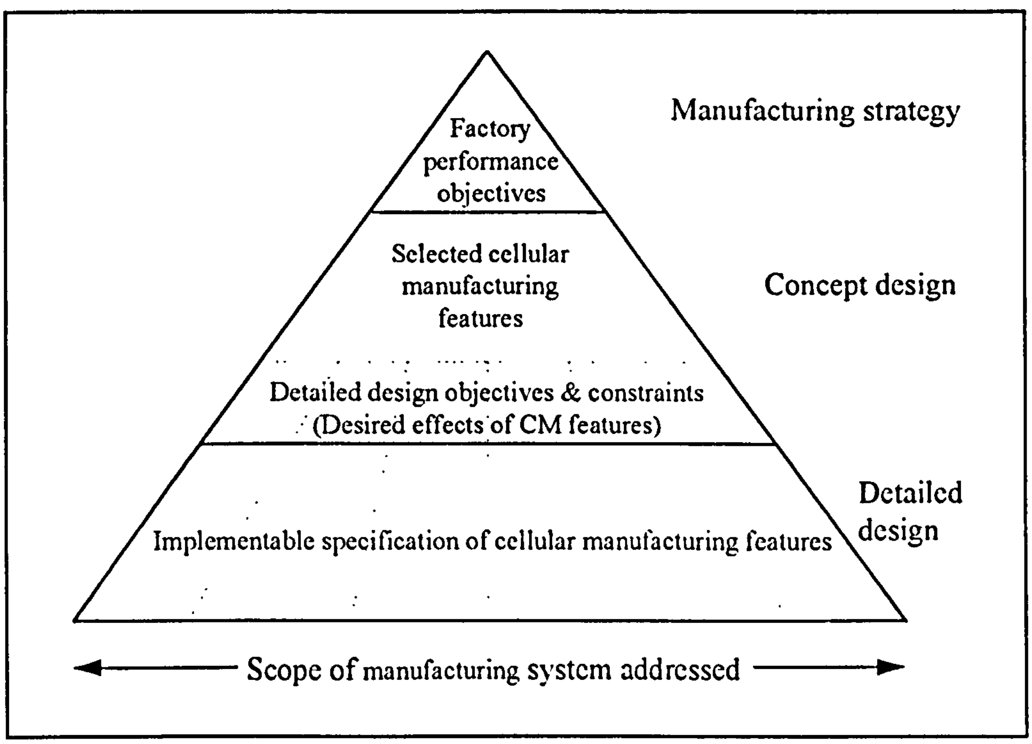


Figure 4.3 The Hierarchy of Design Activity

Figure 4.3 illustrates the nature and role of concept design in relation to manufacturing strategy and detail design. Concept design is the interface between manufacturing strategy formulation and detailed design, translating abstract system wide requirements into tangible sub system features and design objectives. For example, strategic production performance requirements (such as reduced lead time, improved delivery, reduced cost and improved quality) and the system wide concept of cellular manufacturing are cascaded into a compatible set of sub system features and design requirements (such as operator inspection, reduced batch sizes, multi-skilling, reduced set-up times, increased accountability, and increased visibility of performance).

A system wide concept design stage is compatible with Ackoff's (1981) view, that the more parts of a system and levels of it that plan simultaneously and interdependently the better. As cellular manufacturing has been identified as a system wide concept, and the manufacturing systems are complex interrelated sub systems, the concept design stage is also valuable for enabling the ramifications of cellular manufacturing to be understood. This is important because it makes the mechanisms by which performance will be improved explicit. Principle mechanisms can be identified and attention focused on making these happen and ensuring that there are no major conflicts with other elements of the manufacturing system, that might inhibit their operation. Understanding the interrelationships between cellular manufacturing features also provides more specific objectives and constraints to guide the detailed design of individual features. For example, if it is known that reduced set-up times are being pursued primarily to allow smaller batch sizes, then point of use storage of tooling will probably be a more viable option than controlling and kitting tools centrally.

The implication for the composition of the design team of a system wide concept design is that a multi-functional team would most likely be appropriate. This is compatible with the systems methodologies reviewed.

The fact that the relationships between cellular manufacturing features and their effects are not well defined makes the design task more difficult. Mitchell (1991) shows how complex objectives and incomplete theory affects the approach that should be taken to the design task: see Figure 4.4. This is also consistent with Ackoff's (1981) approach to the development of complex systems.

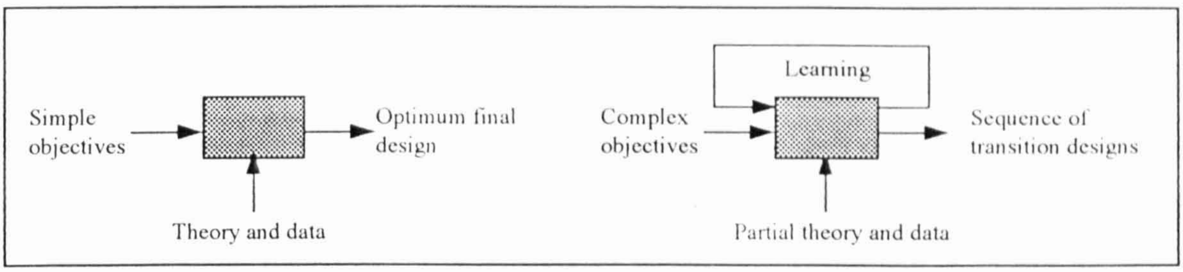


Figure 4.4 Alternative Design Strategies

The development of the manufacturing system should therefore progress as a series of small iterations between design and implementation to provide for learning, and to accommodate evolving objectives. Following this model, the prioritising and selection of cellular manufacturing features from a general model can be considered to be the identification of viable intermediate states on the path to an ideal manufacturing system. Therefore, not every aspect of the manufacturing system needs to proceed for detailed design, just those that have been identified to be important during concept design.

The overall design process proposed for designing cellular manufacturing systems is presented in Figure 4.5 below. Essential inputs to the process are a decision to introduce cellular manufacturing, and the strategic performance improvement objectives that are sought, and the performance and constraints of the current system.

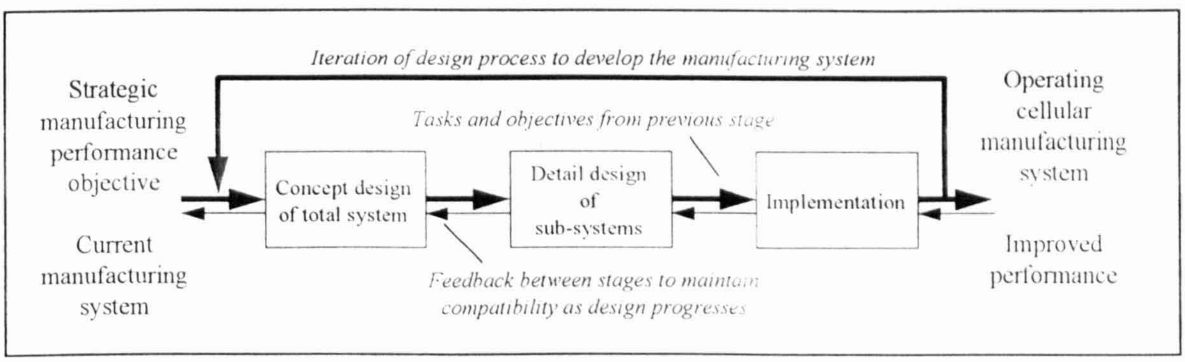


Figure 4.5 An Improved Process for Designing Cellular Manufacturing Systems

As with systems engineering, a problem solving process is an appropriate way of addressing the problems identified throughout the process. Each stage assesses the current situation, defines objectives relevant to the level of detail being considered, and generates, analyses and evaluates solution options before deciding and presenting the solution as the task for the next stage of the process. Iteration will also occur at other levels of the design process. Feedback will occur between process stages when the activity of the down stream process raises issues that affect the definition of the previous stage. For example, detailed design of set-up procedures may indicate the need for changes to the layout and production control system. Similarly implementation is likely to reveal constraints that were not apparent during design. Having successfully implemented the specified cellular manufacturing features, development of the manufacturing system will proceed as further iterations through the overall process. This will enable additional cellular manufacturing features to be selected as they become necessary to continue improving performance. It also allows the emphasis of the design to be modified to maintain alignment with any changes in the drivers and constraints (performance objectives, technology, culture etc.).

Figure 4.6 shows how a cellular manufacturing system is developed through repeated iterations of the design and implementation process. This can be likened to the solution of a jigsaw puzzle. The first pass of concept design might select the corner pieces, and having found three of the four, detail design would identify which corners they were and implementation would put them in place. Having got this far, one would return to the pieces, to find the final corner and to begin selecting the edge pieces (possibly restricting the selection to a particular colour or other feature of the image). Building up from the corners, these pieces would in turn be identified more precisely and then located. A similar procedure would be repeated until the image was complete. For a cellular manufacturing system, early features might include grouping parts machines and operators, collocating cell equipment, and introducing flexible working agreements. Subsequent stages will build upon the new organisation. For example, in the next stage of development, part machine grouping may be refined in light of experience, and training budgets may be increased and devolved to the cell leaders to help increase multi-skilling. In addition, WIP locations may be identified to increase visibility of WIP build up, and performance may be measured for each cell. A third pass might include changing performance measures to remove conflict between measures encouraging output and the requirement for controlling WIP, and set-up reduction may be pursued to eliminate another barrier to further WIP reduction. Development of the manufacturing system will continued in this manner until further application or refinement of cellular manufacturing features is no longer the most expedient way to improve performance.

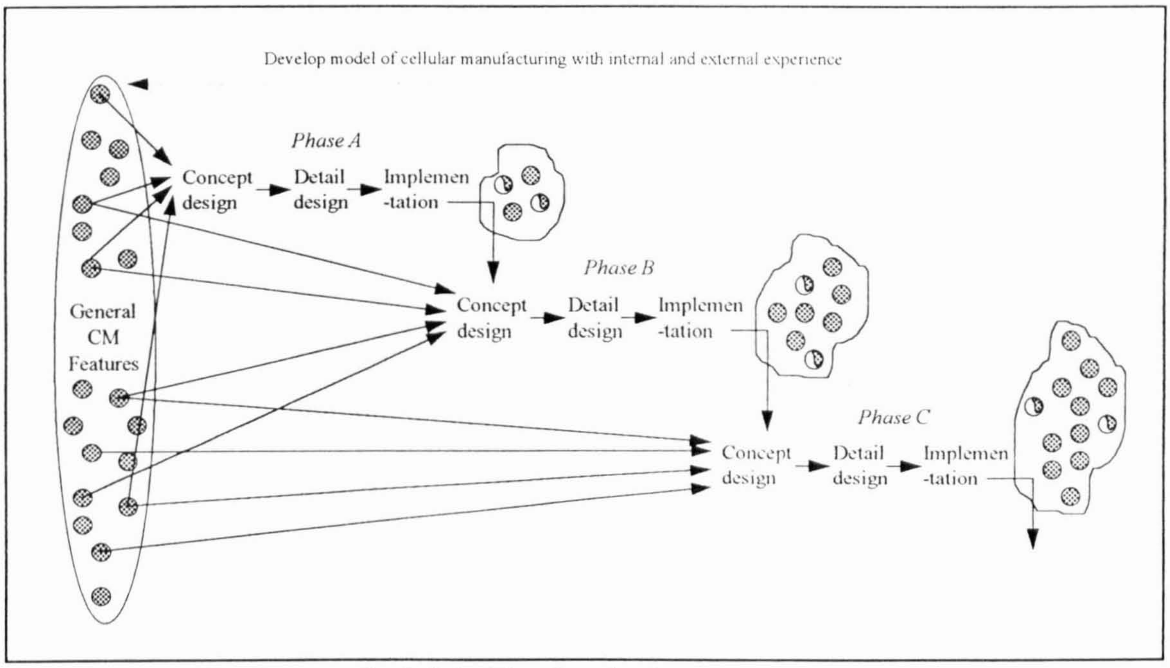


Figure 4.6 Development of a Cellular Manufacturing System

Since concept design has been neglected in the literature concerned with designing cellular manufacturing systems Section 4.5 below will develop these generic process stages in terms of the specific task of generating a cellular manufacturing concept design.

Socio-technical theory argues that the design process should be compatible with the objectives of the design. As team working, and participation in continuous improvement are significant elements of the general cellular manufacturing concept it is likely that these characteristics should be apparent in the design process. A high level of participation is also implied by the principle of minimal critical specification. The learning design cycle described above both supports these principles as operators will be incorporated in the learning process. The separation of concept and detailed design also facilitates the devolution of detailed design to those who will have to implement and operate the design.

4.5 Concept Design

Having decided that cellular manufacturing is an appropriate form of organisation for a given production system, concept design is necessary to tailor the generic concept to a given situation. This involves determining the relative importance of the cellular manufacturing features and selecting an appropriate sub set for detailed design and implementation. The stages involved in this process are described below.

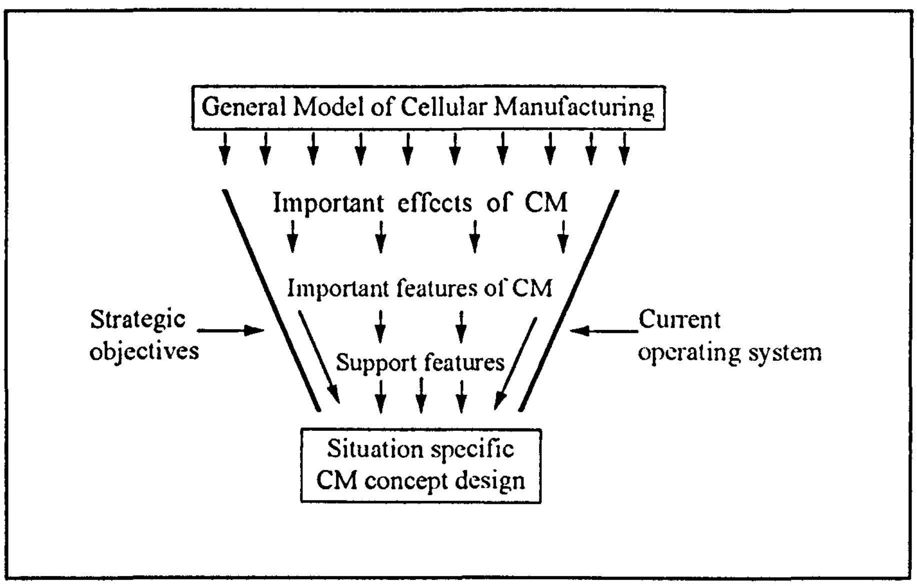


Figure 4.7 Tailoring the Cellular Manufacturing Concept

i Because the general model of cellular manufacturing is not static, but evolving with developing theory and practice, it is necessary to confirm and, if required, update the general model. Reviewing literature and study visits to cellular manufacturing implementations are important activities towards this end.

ii. The route to improved performance will depend on the specific objectives and the performance inhibitors of a given production system. For example, the importance of reducing set-up times would depend on current set-up times and the variety of products made. The process must therefore assess the anticipated effects of cellular manufacturing against the current production system to estimate the impact of these effects on the system's performance. Targets can then be set for the level of effects needed to provide the desired performance improvements.

iii. Although a cellular manufacturing feature may be associated with a desired effect, the level of effect generated is likely to vary with the circumstances to which it is applied. Collocation of equipment will have a greater effect on the visibility of progress in a large factory that has each department in a different building, than it will in small one that is all under one roof. Therefore, it will be necessary to assess features against the current production system to identify their potential influence.

iv. The importance of a particular cellular manufacturing feature will be a function of the benefit that the feature generates and the difficulty of introducing that feature. The benefit will be a function of the number of effects it generates, the scale of these effects and the importance of these effects to improving the company's strategic performance. It is likely that there will be more than one dimension to strategic performance that will need to be accounted for in assessing the importance of cellular manufacturing effects.

Having identified the primary cellular manufacturing mechanisms for achieving the desired objectives, it might then be necessary to identify the effects of further cell manufacturing features, the main function of which are to either, enable the primary mechanisms, or to mitigate any of their unwanted side effects. For example, where batch size reduction is identified as a primary mechanism for WIP and lead time reduction, support features may be required to negate the associated increase in the number of set-ups, number of inspections, and amount of documentation.

v. Having established the relative importance of the various cellular manufacturing features to the achievement of performance objectives and their support requirements, an appropriate selection can be made for progressing to detailed design and implementation. The effects required from each feature, and its contribution to the target can be defined, along with the relationships between features.

Lack of formal recognition of this stage in the design of cellular manufacturing systems means that it currently relies on the experience of cell designers or trial and error. From the description of the process stages above, concept design can be seen to be a complex and creative task. It is not surprising that companies find concept design difficult. Many tools and techniques exist to address elements of the detailed design, however there is a lack of support for concept design.

4.6 Summary

An improved process for designing cellular manufacturing systems has been outlined, that builds upon the general model of cellular manufacturing defined in Chapter 2. The novelty of this approach stems from the treatment of cellular manufacturing as a general set of system wide features that must be tailored to meet specific circumstances. This leads to the emergence of concept design as an important and neglected stage in the design process, and therefore, to the specification of a procedure for performing this task. The key issues raised are highlighted below:

- The approach should provide guidance to the designer as to what manufacturing system features are compatible with the principles of cellular manufacturing without being prescriptive. A procedure based on tailoring an ideal or general model to a specific set of objectives and circumstances satisfies this requirement.

- Cellular manufacturing is a system wide concept, and the design process must define the organisation of the value adding function and its interfaces with all of the elements of the manufacturing system that are affected by cellular manufacturing. This is defined by the range of features that are generally associated with cellular manufacturing. Chapter 2 and Appendix A provide a current reference set of features, which have been compiled from an extensive review of theory and practice.

- The design task is decomposed using the systems life cycle, and design detail to establish a process that incorporates a system wide concept design stage. The purpose of this stage is to select an appropriate sub set of cellular manufacturing features prior to undertaking detailed design of the chosen features. The design is developed iteratively, by identifying the highest priority features, specifying these in detail and implementing them. Then, in light of the effect on the production system and its performance, returning to reconsider the relative priorities of the cellular manufacturing features and make a new selection, followed by detailed design and implementation. Development of a system wide concept design would be best undertaken by multi-functional teams that incorporate system users.

The task of concept design is to identify important features from the general model and define the effects required of the selected features. The process stages for concept design have been specified in this chapter. However, as this stage has been neglected in the literature concerned with designing cellular manufacturing systems there is a lack of tools and techniques available to assist with this stage of the design. Chapter 5 will present a mechanism to support the development of a concept design for cellular manufacturing. Chapter 6 will describe an industrial application of this process.

Chapter 5 Procedure for Cell Manufacturing System Concept Design

The objective of this chapter is to develop a tool to support the concept design stage of the process for designing cellular manufacturing systems established in Chapter 4. The purpose and requirements of the tool are developed from the process definition and the insight gained through reviewing the theory and practice of cellular manufacturing and the design of cellular manufacturing systems.

5.1 Introduction

Concept design is the development of the general model of cellular manufacturing into an explicit statement of the cellular manufacturing features and effects that will provide the desired improvements in performance for a given situation. It is an important stage in the design process because it provides direction for detailed design and implementation, and ultimately determines the success of the manufacturing system developed.

The concept design process has been described in Chapter 4. The essence of this task is to relate the company's strategic objectives to the various features of the general cellular manufacturing model and select the most important cellular manufacturing features. However, because of the nature of cellular manufacturing this is not straightforward. The main difficulties associated with this task are listed below.

i. The relationships between cellular manufacturing features and their effects is not well defined. First, there can often be more than one explanation for the benefits derived from a feature. Second, relationships are generally non deterministic. The particular effects that will be derived from cellular manufacturing features must be estimated for each specific situation, often by subjective judgements.

ii. The relationships between the features of cellular manufacturing and the performance of the production system are complex. There are long chains of cause and effect between the actual changes made to the production system features and changes in strategic performance. This, combined with the fact that the relationships between cause and effect are many-to-many, gives rise to interrelationships. Interrelationships mean that the effect of applying a particular feature will depend upon the nature of the rest of the production system.

As concept design is not explicitly recognised by the majority of design processes for cellular manufacturing it is not surprising that there is an equal deficit of tools and techniques to support this task.

5.2 Use of Matrices for Relating System Features to Performance

Mizuno (1988) identifies matrices as an appropriate tool for indicating the presence and degree of strength of (many to many) relationships between two sets of factors. Various patterns of matrices can be constructed to tackle a range of problem situations. A notable application of matrices for relating system features and performance in the design of complex systems is quality function deployment (QFD).

QFD is a practical design tool for helping designers to cascade customers requirements for product quality to all decisions concerned with the design of a product and its manufacturing process (Eureka and Ryman 1988). Hjort, Hananel and Lucas (1992) explain that the purpose of QFD is to organise large quantities of data from all stakeholders in a product development project in order to identify the critical parameters that need to be controlled to improve performance against customer requirements. The insight is deployed through the development process so limited resources are focused where they will have the greatest impact on customer satisfaction. Descriptions of QFD matrices and procedures can be found in Akao (1990), ASI (1989) and Hauser and Clausing (1988). QFD provides the following benefits to the design processes:

- Focuses design on customer requirements, and competitive performance.
- Provides a forum for multi-disciplinary communication.
- Deals with complex interrelationships between design parameters.
- Structured approach to defining critical characteristics.
- Concentrates efforts upstream in the design process, to anticipate and prevent problems arising later.

These points are elaborated in Appendix D. As can be seen from section 5.1 there is a significant correspondence between these benefits and the difficulties identified with developing a cellular manufacturing concept design. This indicates that a matrix method could be usefully developed to harness similar benefits for the design of cellular manufacturing systems.

While QFD was developed to support the design of products and their associated manufacturing processes, Burn (1990) suggests that the use of QFD is not restricted to the design of physical products and that it would be equally applicable to the running of a business. However, there are only a few examples of broader applications of QFD. Maddux, Amos and Wyskida (1991) report the successful use of QFD to clarify objectives and define a strategy for the provision of production engineering tools by the Production Engineering Division of the US Army Missile Command. Conti (1989[a]; 1989[b]) proposes the use of QFD for managing the integration of processes: the objectives for the total stream of processes being cascaded through QFD matrices to the sub processes.

Matrices in general have also been applied to the design of manufacturing systems. Sweeney (1992) uses a matrix to relate various manufacturing tools and techniques to a company's desired competitive capabilities, and a matrix is also used in the DTI Competitive

Manufacturing Strategy procedure (DTI 1988) to present the relationships between elements of the production system and manufacturing capability.

5.3 Development of a Matrix Approach for Cellular Manufacturing Concept Design

5.3.1 Assessing the Potential for Direct Application of QFD

Initially, QFD was taken as a starting point for exploring how to support concept design. Two academics involved in the same industrial case to introduce cellular manufacturing agreed to participate in an exercise to follow the QFD process stages using the case to provide some tangible basis for design decisions. Two half day sessions were arranged. The author facilitated the proceedings based upon the process defined by the American Supplier Institute (1989). After completing the first stage of QFD, the participants reviewed the results. The participants were satisfied that the performance improvement priorities generated by the process adequately reflected the cases requirements, the following observations were made:

- Clarification and communication of strategic objectives was encouraged.
- Assumptions about the causes and potential solutions to problems were surfaced for analysis.
- The process provides a logical procedure for prioritising change opportunities.

However, the process was found to have the following short comings:

- Different levels of objectives and solutions were generated during the process because their was insufficient guidance as to what was an appropriate input for a given stage in the process.
- Assigning strengths of relationships time was consuming, and became tedious, though it also generated useful debate.
- The secondary triangular QFD matrix used for exploring the interrelationships

between design decisions was also time consuming. This problem was diminished by only identifying interrelationships that impinged on important design decisions. However, due to the complex interrelationships in a manufacturing system, this matrix soon became unintelligible.

It was concluded that basic matrix mechanism underlying QFD would be useful in supporting the concept design of a cellular manufacturing system, but it would need to be incorporated into a new procedure, developed specifically this purpose. In particular construction of the matrices should be based upon defined features and effects of cellular manufacturing, such as those presented in Appendix A.

5.3.2 A New Matrix Based Concept Design Procedure

Cellular manufacturing concept design requires strategic performance requirements to be related to the features of cellular manufacturing. However, the relationship between these is complex and indirect, acting through a range of interrelated, intermediate effects. Two matrices can be used to make this logic explicit, one connecting features to their effects and the second connecting these effects to desired strategic performance improvements.

Chapter 2 identified that while some features of cellular manufacturing will have a desirable effect on certain aspects of performance it may not be practical to introduce them to a production system in isolation. They might have undesirable side effects that need to be mitigated. For example, set-up time reduction, collocation of resources and simplified paperwork may be necessary to minimise the negative effects of reducing batch sizes. Having identified the primary features that are required to address the desired performance improvements it will then be necessary to review these to determine their support requirements. Supplementary features can be identified to provide the necessary effects that are not met by the primary features. Figure 5.1 shows an overview of this process. The construction and use of these matrices is described in more detail below.

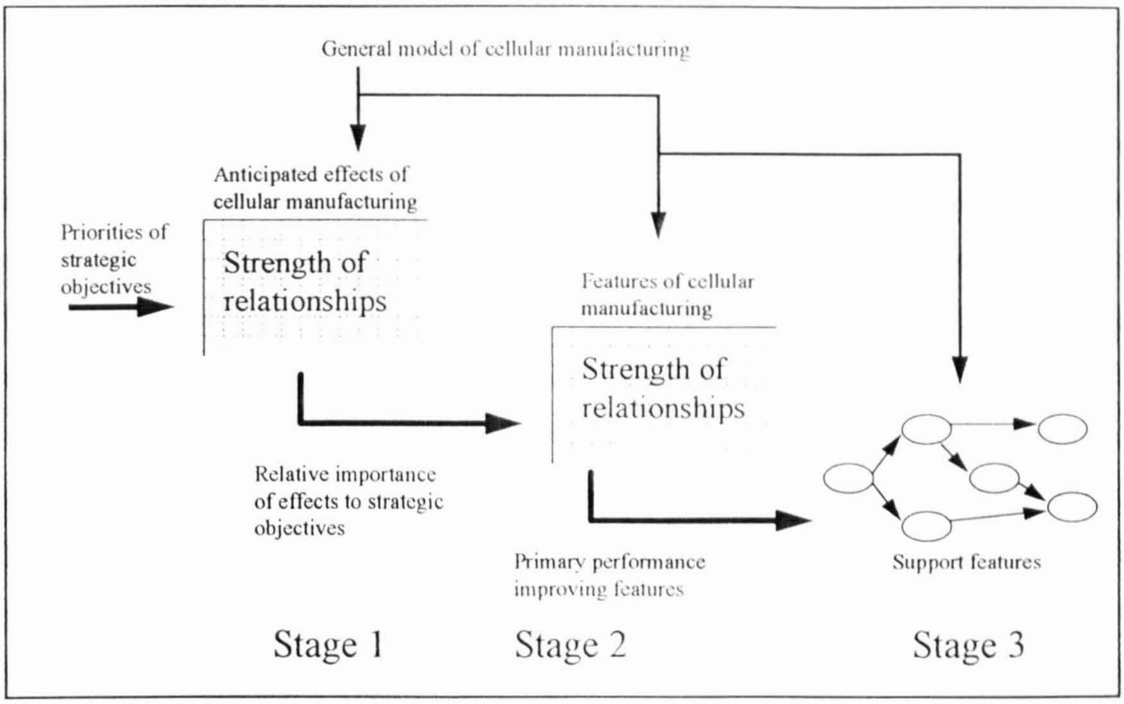
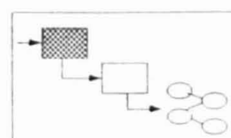


Figure 5.1 Use of Matrices for Cellular Manufacturing Concept Design

Concept Design Stage 1: Identify Important Cellular Manufacturing Effects



The purpose of the first stage is to determine the relative potential impact of the effects of cellular manufacturing upon strategic performance so that important effects can be identified for further analysis. The following steps are required:

a. Construct a matrix with strategic performance objectives along the vertical axis and the possible effects of cellular manufacturing along the horizontal axis. The set of effects is consolidated from the effects associated with all the features in the general model of cellular manufacturing. A generic matrix is presented in Figure 5.2

b. Confirm strategic performance improvement priorities, and weight the parameters between one and ten, where ten is the most important.

c. Appraise the current manufacturing system to assess the potential impact of each effect upon the strategic performance parameters. Insert a score in the

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Potential Effects of Cellular Manufacturing

Strategic Manufacturing Performance Improvement Objectives	Priority Weighting	Reduced processing variables	Increased consistency of production	Reduced scrap	Reduced damage	Improved workmanship	Enabled problem solving	Improved problem solving	Reduced version control and obsolescence	Reduced time to identify and isolate defects	Reduced processing of defective items	Increased visibility of system problems	Improved accountability for performance	Enabled delegated decision making	Increased perception of task significance	Improved morale and satisfaction	Increased part familiarity and reduced start ups	Increased cell autonomy	Improved team and territory definition	Increased operator commitment	Reduced absenteeism	Reduced labour turnover	Increased motivation	Improved communication / feedback	Timely implementation of shop floor suggestions	Simplified material flow	Reduced information/documentation requirements	Enabled simplified production planning & control	Reduced PPC staff	Reduced queuing	Reduced WIP	Reduced expediting & WIP tracking	Encouraged low WIP	Reduced space required	Discouraged over production	Reduced shortages	Improved visible control	Reduced impact of breakdowns	Encourage factory level performance improvements	Reduced load surges	Improved realism of planning and customer promises	Increased speed and timeliness of replanning	Reduced process planning effort	Increased standardisation of job times	Enabled simplified cost accounting	Improved job estimating	Reduced number of set ups	Reduced setting up times	Increased opportunity for pre-setting	Enabled set-up based sequencing	Increased maintenance resource	In cycle maintenance enabled	Reduce unplanned downtime	Improved maintenance scheduling	Enabled maintenance planning	Encouraged team working	Increased flexibility of job assignment	Reduced waiting time	Encouraged flexible working	Encouraged multi-skilling	Increased multi-skilling	Improved labour efficiency	Reduced storage and retrieval complexity	Increased opportunity for incycle operations	Reduced number of operations	Improved career development options	Reduced number of tools / tooling costs	Improved IR	Reduced material handling	Reduced unnecessary operator movement	Improve interpersonal / groupworking / problems solving	Improved health and safety	Improved foundation for evolution of automation	Increased market opportunities	Reduced investment	Increased flexibility for redesigning cells				
Improved quality																																																																																
Improved delivery lead times																																																																																
Improved delivery reliability																																																																																
Improved volume flexibility																																																																																
Increased product flexibility																																																																																
Reduced cost																																																																																

Figure 5.2 Generic Matrix for Determining the Important Effects of Cellular Manufacturing

appropriate matrix location according to the scale of potential impact. Use one for low impact, three for medium and nine for high. (This choice of scoring system is based on its almost universal adoption by QFD users.)

d. Calculate the relative strategic importance of effects as follows. For each effect, multiply the scores of impact potential with the weights of strategic objectives, and sum these calculations. The procedure is repeated for all the effects. The score for each effect can then be normalised back to a value between one and ten.

e. Identify those effects that are critical to achieving the desired improvements in the performance of the manufacturing system, and which should be taken into the next stage of the method to identify which are the most important cellular manufacturing features.

Figure 5.3 illustrates the construction of a matrix for relating strategic performance improvement priorities to the effects of cellular manufacturing. In the partial example shown, the highest priority objectives are reduced lead time followed by reduced cost. The priority effects to be achieved start with improving accountability for performance and reducing WIP, followed by reducing set-ups and reducing defects. Selection of effects to be pursued in the next stage follows common sense application of the pareto principle.

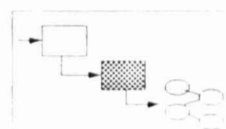
Potential Effects of Cellular Manufacturing

Strategic Performance Improvement Priorities		Imp'd accountability for cost, quality & delivery	Reduced expediting and WIP tracking	Reduced WIP / queuing	Improved morale & job satisfaction	Enabled problem solving	Reduced set up times	Reduced defects		
Reduced Lead time	10	9	0	9	1	3	9	5		
Reduced Cost	7	9	9	9	0	3	5	9		
		153	63	153	10	51	125	113		

Figure 5.3 Construction of a Matrix to Identify Important Effects of Cellular Manufacturing

This stage of the concept design process focuses attention upon those effects of cellular manufacturing that are most significant for achieving the desired performance improvements. This minimises waste effort in pursuing process improvements that will only have a marginal effect on strategic performance. Clarifying what are the primary drivers for improving strategic performance provides a sound basis for assessing the benefits of cellular manufacturing features later in the design process. It also provides some guidance for developing the detailed design. For example, if reduction of inspection delays to reduce lead time is the main reason for pursuing source inspection, this will strongly influence any debate as to whether work should wait between processes for inspector verification.

Concept Design Stage 2: Identify Important Cellular Manufacturing Features



Stage 2 determines the relative contribution of cellular manufacturing features to the desired effects. This enables the identification of those features that, if applied to the production system in question would best provide the desired effects identified in the previous section. The procedure is similar to that for stage one.

a. Construct a matrix with the effects of cellular manufacturing and their scores of strategic importance in descending order down the vertical axis, and the possible features of cellular manufacturing across the horizontal axis. Figure 5.4 presents a proforma for this stage. The vertical axis is to be populated with the desired effects identified in stage 1.

b. Appraise the current manufacturing system to assess the potential impact of each cellular manufacturing feature upon the important cellular manufacturing effects identified in stage one. Insert a score in the appropriate matrix location according to the scale of potential impact. Use one for low impact, three for medium and nine for high.

Possible Cellular Manufacturing Features	Desired Effects of Cellular Manufacturing																				
Importance																					
Inc'd dedication of resources to similar parts																					
Inc'd ownership of products																					
Inc'd ownership of resources																					
Inc'd dedication of teams																					
Inc'd distribution of support																					
Inc'd collocation of resources																					
Red'd distance between machines																					
Inc'd definition of physical cell boudary																					
Inc'd point of use storage of raw materials																					
Inc'd point of use storage of tools																					
Inc'd point of use storage of finished products																					
Inc'd multi machine manning																					
Inc'd in-cycle ancillary operations																					
Inc'd multi-skilling / flexible working																					
Inc'd operator material handling																					
Inc'd shop floor problem solving																					
Inc'd job satisfaction																					
Inc'd use of SMED																					
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Inc'd use of simple small duplicate machines																					
Inc'd standardisation of tooling																					
Inc'd customisation of handling devices																					
Inc'd devolution of maintenance responsibilities																					
Inc'd TPM / preventitive maintenance																					
Improved housekeeping																					
Inc'd operator responsibility for housekeeping																					
Red'd number of job grades																					
Inc'd rewards for knowledge /skills																					
Red'd piece rate rewards																					
Inc'd team based rewards																					
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Inc'd devolution of training responsibility																					
Inc'd flatness of management organisation																					
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Inc'd devolution of scheduling																					
Inc'd simplification of planning and control																					
Inc'd use of visual systems																					
Inc'd use of pull control / local WIP regulation																					
Single cycle ordering																					
Red'd batch sizes																					
Inc'd devolution of inspection responsibility																					
Inc'd inspection throughout process																					
Inc'd use of Poka Yoke																					
Inc'd devolution of PM responsibility																					
Inc'd publication of results																					
Inc'd link between PMs & customer satisfaction																					
Inc'd & earlier involvement of manuf in design																					
Inc'd direct delivery to point of use																					
Inc'd direct ordering of supplys by user																					
Inc'd matching of production rate to demand																					
Inc'd direct contact with customer																					

Figure 5.5 Generic Matrix for Determining Important Cellular Manufacturing Features

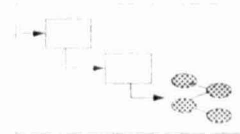
c. Calculate the total relative importance of the features for achieving the desired effects. For each feature, multiply the score of potential impact with the score of importance for the related effect then sum the results of these calculations. This procedure is then repeated for all features that generate a desired effect.

d. Select high scoring cellular manufacturing features as primary features making sure that a significant impact is identified for each of the most important effects.

Continuing with the example used in Stage 1 above, typical cellular manufacturing features that might be identified as having a strong relationship with improved accountability for performance are increased ownership of product, resources and increased dedication of team members and increased distribution of indirect tasks. Reduced work in progress and queuing would typically have a strong association with increased devolved scheduling, visual control systems, pull control, increased multi-skilling and flexible working, and in cycle inspection.

This stage performs the central function of concept design. It assembles those features of cellular manufacturing that are most likely to bring about the effects of greatest importance to the achievement of the company's strategic performance improvement priorities. Together with the stage one, this defines the logic of how the company in question expects to use cellular manufacturing to improve performance. The aim of making this logic explicit, is to enable criticism and improvement of the proposed design concept. It also forms the basis for detailed design, informing the detailed design of each feature with specific objectives and awareness of interactions with other features. In addition, understanding the link between features and strategic benefits can be useful for justifying the cost of introducing features. However, there is a degree of refinement required to make sure the design is viable. This is addressed in stage three below.

Concept Design Stage 3: Determine Supplementary Support Features Required and Presentation of the Concept Design



The objective this stage is to identify any difficulties there might be with introducing the selected features, such as undesired side effects that need to be mitigated, or inappropriate conditions that would prevent a feature from being implemented or having the desired effect. It is assumed that if the primary features have formed a part of other cellular manufacturing implementations then any additional features that were necessary to enable them are likely to have been incorporated into the cellular manufacturing model.

a. Appraise each selected primary feature to identify any additional requirements necessary to enable them. For example, reducing batch sizes may require that SMED set-up procedures are introduced and machines collocated. Implementing in-cycle inspection may necessitate operator self inspection.

b. Once all the required support effects have been identified, then establish which will be provided by the primary feature set and which will need additional features to ensure all the primary features are viable. These additional features should be sought in the general set of cellular manufacturing features.

c. Finally there is a need to present the selection of features, their intended effects, and required support features in order to inform detailed design and implementation. The primary requirement is to present any precedencies that exist between the various features chosen. Therefore, a network or PERT type diagram is appropriate for this task. Figure 6.2 shows a network diagram being used to present selected cellular manufacturing features and their interrelationships.

This stage aims to encourage debate to determine what is required for the primary features to work. It also endeavours to communicate the intention to take appropriate action to enable the primary features, thus dismissing any concerns or arguments over their validity. The insight presented by this stage is also available to justify the introduction of cellular manufacturing features that may not have a significant direct impact upon strategic performance.

5.4 Summary

Tailoring the general concept of cellular manufacturing to suit the circumstances of a specific manufacturing system is an important but neglected stage of designing a cellular manufacturing system. The main difficulties are associated with understanding the relationships between cellular manufacturing features and desired performance improvements. This is complicated by the ill defined and complex nature of the cellular manufacturing concept.

Matrices have been identified as an appropriate mechanism for presenting many to many relationships between two sets of features. QFD has been identified as a widely known and successful example of the use of matrices for designing complex systems. The benefits of using this methodology for designing products correspond to the difficulties of developing a cellular manufacturing concept design, though it has not been found to be suitable for direct application to this problem.

A new procedure, using matrices specifically to support the concept design stage of the process for designing cellular manufacturing systems defined in Chapter 4, has been developed and presented. It takes the general set of cellular manufacturing features, described in Chapter 2 and summarised in Appendix A, as its starting point, and then tailors this to suit a specific set of circumstances. Two matrices are used to relate the features of cellular manufacturing, through their effects upon the existing production system, to strategic performance improvement objectives.

The method comprises three main stages:

- The first matrix relates strategic manufacturing objectives to the effects of cellular manufacturing. Important effects are identified and cascaded to the second stage for further analysis.

- The second matrix relates important effects to the features of cellular manufacturing. Those features that will have the most significant impact on the desired effects are determined.

- The third stage identifies the additional support features that are necessary to enable the primary features to be implemented. The interrelationships among the various features are presented using a network diagram.

Chapter 6 Review of the Cellular Manufacturing Concept Design Process

The objective of this chapter is to present a validation of the new approach to designing cellular manufacturing systems. Application of the method in an industrial situation is described and the impact of the method is discussed. Benefits and problems encountered while using the method are presented. The method is also appraised by experienced consultants and cellular manufacturing practitioners. Support is sought, for the pertinence of the flexible general model of cellular manufacturing features and effects, for the overall design process, and for the matrix based concept design procedure.

6.1 Introduction

This chapter describes how the new method for designing cellular manufacturing systems was tested and developed. As described in Chapter 5, initial development and testing of the procedure for supporting concept design was undertaken at Cranfield. Parts of the method were worked through hypothetically by academics with an interest in cellular manufacturing systems to test its logic and assess its viability. Feedback from these sessions was incorporated into the development of the method, so that it was defined sufficiently for presentation to a wider audience and for application in the industrial case.

The main vehicle for testing was an industrial case study to introduce cellular manufacturing. One of the key reasons why the Cranfield Manufacturing Centre were asked to do the work was because the company were reassured by the approach proposed by Cranfield, and in particular the flexible system wide concept of cellular manufacturing that was advocated. The process was applied in the live situation of the case. Having completed and presented the concept design to the company, the design process was reviewed. The review involved direct reflection on the design process by the author and a series of semi-structured interviews with the process participants. The prompt sheet for the interviews can be found in Appendix F. There were two main categories of interviewees: first, the company personnel that were central to the cellular manufacturing project, and second, the Cranfield staff and manufacturing consultant that participated in the case.

The above mentioned Cranfield staff and manufacturing consultant had wider experience of designing cellular manufacturing systems that enabled them to comment on the extent to which the findings from this case could be generalised. The external validity of the research, was strengthened further by presenting the method to additional consultants and industrialists with experience of designing cellular manufacturing systems for their opinion on its applicability and value. The industrial case is described in sections 6.2, 6.3. Results and reflections on the design process are discussed in section 6.4.

6.2 Industrial Case Study

6.2.1 Company Background

The company is a subsidiary of a large British engineering company. It is approximately a £9M business (though most of this is value added as the majority of their current business supplies free issue[1] material), employing around 200 people. The primary products are nozzle guide vanes and turbine blades for the gas turbine industry. These are complex precision components that require multi-axis grinding and advanced manufacturing processes such as electro-discharge machining and laser drilling. They have small bills of material, generally comprising one or two main castings and sometimes one or two additional components such as small tubes or plates.

[1] Free issue refers to material for processing by a supplier or sub-contractor, which is provided free of charge by the customer.

The company are a sub-contract manufacturing business with no design engineering capability. One customer, currently dominates their business, though they do supply some other aerospace companies and the industrial gas turbine market. The company live with the expectation that this customer will withdraw business for their own production facility. They are therefore looking to win new business that will reduce this dependence.

The company's business is low volume high variety. Typically they would have around a hundred different part numbers on their schedule at any one time. More specifically, the end products for their components have long life cycles and there is significant visibility of engine programmes even if some of them are intermittent. However, short term fluctuations in these programmes can be quite pronounced. Their role as an off-load subcontractor exacerbates this situation.

6.2.2 The Project to Implement Cellular Manufacturing

During 1994 the company was made aware of two significant new requirements for their major customer. The first was for 50% reduction in lead time, and the second was for the end of free issue material. Reviewing their strategic manufacturing performance requirements, the company reached the following conclusions:

> Lead time reduction is currently their most critical performance improvement requirement. A target has been set to reduce lead times by the order of 50% in response to the direct request from their primary customer. With a large part of their business arising from tactical off-loading by their customers own manufacturing facilities, reducing lead times will also make them more flexible to customer demands and open up more business opportunities. In addition reduced lead times will also support their efforts to win business beyond their dominant customer.
>
> The second most important improvement requirement is that of cost reduction, to reduce the impact of their impending liability for the cost of inventory, in

anticipation of the change away from free issue material. Any new business with other companies is likely to be based on fully bought out material rather than free issue, so this change in performance will also prepare the company for entry to a wider market.

Quality is an order qualifying performance characteristic in the aerospace industry, and the company's quality performance is considered to be satisfactory by their customers. However, they are aware that their cost of quality is high.

The company had identified cellular manufacturing as an approach to production organisation with a reputation for enabling significant reductions in lead times and work in progress. The Cranfield Manufacturing Centre became involved in May 1995 to provide support and guidance to help define a cellular manufacturing system to achieve this objective. In line with the process for designing cellular manufacturing systems presented in Chapter 4, Cranfield proposed the following project outline.

1. Review of current system and concept design
2. Detailed design
3. Implementation
4. Audit performance and review design

A project team was set-up to support the execution of this process. The core team comprised the company's manufacturing director and two Cranfield University members, and a consultant from Cranfield Innovative Manufacturing. Additional members were drafted in as needed to support specific tasks and analyses. The main role of the core project team was therefore to determine the timetable of process, initiate design activities and recruit temporary project team members, and communicate a coherent picture of the development of the design. Formal communications included news letters, presentations, and forums to supplement informal mechanisms.

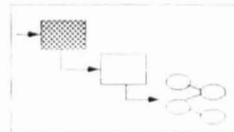
The project was initiated in May 1995. The first three months were mainly taken up with data gathering, general education about cellular manufacturing, reviewing the existing system and development of the concept design. Detailed design began with part machine grouping as this was required to make the concept more tangible for the company, though layout and cell manning were progressively developed to support grouping decisions. The cellular organisation was presented and accepted in December 1995. Part machine groups, layout and cell teams were refined in early 1996 and further elements of the detail design were initiated, such as SMED analysis of set-up procedures and the generation of appropriate strategies for reducing set-up times. For internal reasons, relocation of machines could not begin until May 1996 and then all machines were moved over a two month period. The company is continuing to detail design and implement the concept design.

This case focuses on the first element of the process and describes its implications for the subsequent stages. Concept design requires a review of the current manufacturing system to determine problems and barriers to improved performance. More specifically the objectives of this analysis are to identify what effects of cellular manufacturing would help improve the company's performance, and to identify what features of cellular manufacturing they could apply to provide the desired effects.

6.3 Concept Design

Cranfield took primary responsibility for concept design, due to their broader experience and depth of knowledge of cellular manufacturing, and because the company wanted an objective assessment of their production system and its performance. The approach taken to concept design followed the procedures described in Chapter 5. The model of cellular manufacturing features and effects was used as a framework for assessing the current manufacturing system. A variety of information sources were exploited, including company data, direct observation, and the experience and opinions of company personnel through attitude surveys, workshops and informal discussions. This was achieved by spending time in the company, observing and questioning features of their current organisation and working methods. This time was also used to introduce their personnel, and the foremen in particular, to the principles and techniques of cellular manufacturing and discuss the potential of these for the company. Their views were then incorporated into the development of the concept design.

Stage 1: Identification of Important Cellular Manufacturing Effects



Following the procedure described in Chapter 5 and illustrated by Figure 5.2, each cellular manufacturing effect was considered in turn to identify those that would improve lead time and cost performance of the company's production system. In effect, the general model of cellular manufacturing effects was used to structure the analysis of the current system's performance. The main findings of this analysis are summarised below.

The company turns its stock over approximately five times a year. As there is very little raw material stored or finished parts, the majority of inventory is WIP. If this is averaged across the work centres, there would be queue of roughly a day in each WIP pool, while the operation time for a part can often be measured in minutes. As there are more work centres than people, some queues will be longer than one day. It is estimated that the value of WIP will double if their entire business is converted to fully bought out material. Reducing WIP can therefore be seen to have a major potential for improving lead times and for reducing cost impact of the move away from free issue material. Simplified production planning and control with reduced WIP was seen as an opportunity for further cost reductions. In addition, the potential for reduced work-in-progress and consequently lead times to reduce the number of defects produced by a faulty process before its consequences were discovered down stream were noted, along with the greater visibility of rework or replacement requirements provided. These last two factors will also set-up a benign spiral as less WIP will be required to buffer against uncertainty.

Reducing set-up times was determined to be an important effect of cellular manufacturing for the company because set-ups consume a significant proportion of their lead time and capacity. It was estimated that approximately 5% of the lead time for a batch of one product would be taken by setting. In addition to the direct consumption of lead time, long set-ups cause a reluctance to break down running jobs and encourages the ganging together of several batches. It also means that small rework batches are delayed waiting for other batches to arrive and make it worthwhile setting the machine. These consequences of long set-up times all further increase lead time and the level of WIP. Setting is also a non value adding activity that only adds costs to the product. Analysis of a typical set-up on a CNC surface grinding machine indicated that over half of the set-up time was taken up by preparation. It was also noted that the CNC programmes need to be adjusted between different machines of the same type. The main elements of the inspection system and quality performance are presented in Figure 6.1 below.

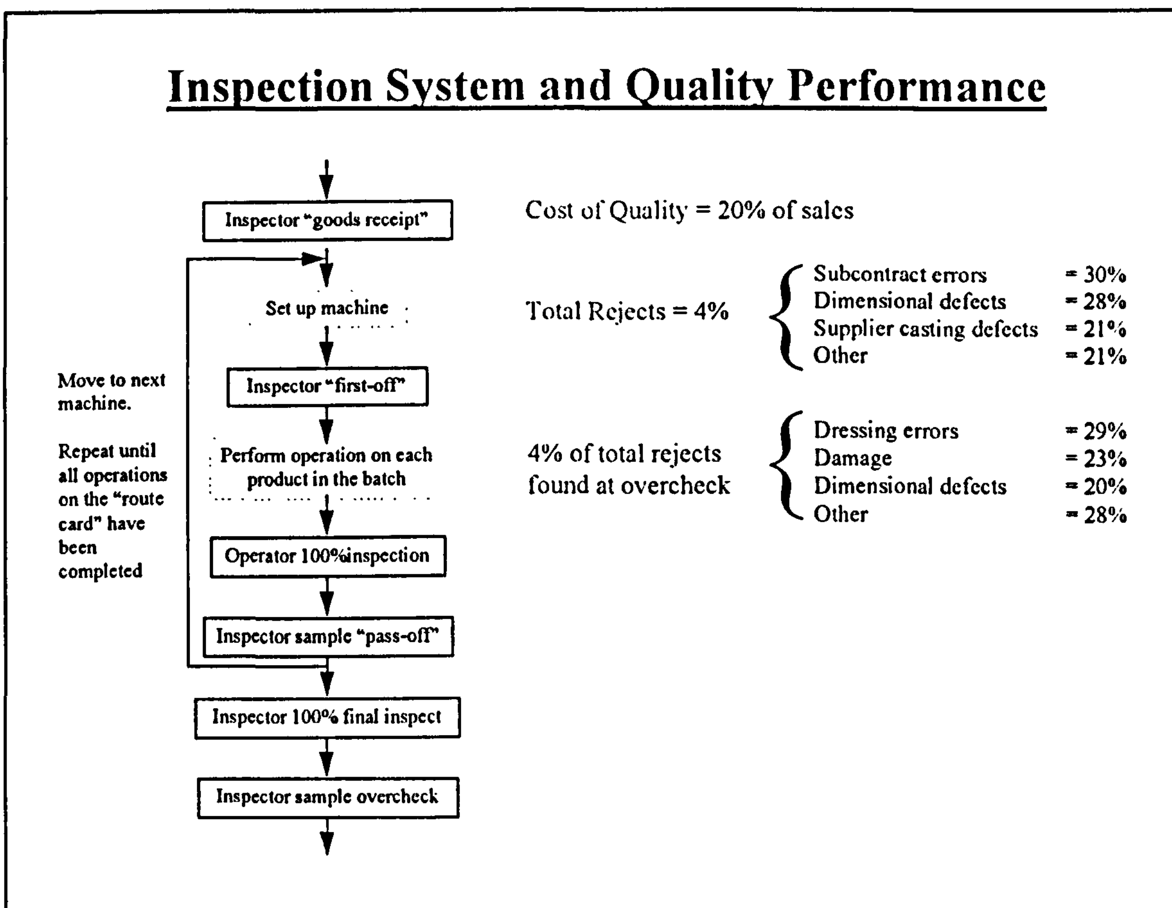


Figure 6.1 Inspection System and Quality Performance

In addition to the operators inspecting every part after every operation, all batches must be "passed off" by a production inspector sampling the batch. The sample is often taken as the batch is being processed to reduce the time taken to identify process abnormalities and to reduce the impact of inspection upon lead time. A batch is not allowed to move on to the next process without a "pass-off", and a process operated by a semi skilled operator will not be set-up for the next part. A "pass-off" is also required at the beginning of each shift because the majority of dimensional errors are attributed to variation in the loading of parts to the fixture. Final inspection is a visual inspection of all parts by semi skilled inspectors. Overcheck completes outstanding paperwork and audits critical dimensions. In reality, overcheck exceed their audit requirements, often doing 100% of pieces. 4% of defects are found at overcheck though these parts will have already been passed by many other inspection stages.

Reducing the amount of defects and stemming the passage of defective items through the system would allow duplicate inspection operations to be eliminated. This would reduce the cost of quality and reduce inspection delays. Improving the reliability of production would also improve average lead times and reduce the need for WIP buffers.

Because many of the company's products are manufactured in ring sets (a circular arrangement of components similar to their assembly in the customers product), the complexity introduced by non-conformances are particularly pronounced. It is desirable to produce parts in full ring sets because quality is more reliable and to achieve maximum efficiency at bottleneck machines. Therefore, the possibility of defects means that a bond of spare parts is held in front of the first radial process to fill in any gaps that arise. However, if any items are lost at a radial process then the batch must proceed as a partial batch. Moreover, if it subsequently decided to rework the part, then it will have to wait for another batch to arrive for processing that is a part short. Reducing defects and reducing the time taken to deal with non conformance would lessen these issues and thereby reduce work in progress, lead times and lead time variability.

The current functional organisation means that no department completes a product. In fact a product will more than likely pass backwards and forwards between departments several times throughout its manufacture. Therefore, it is difficult to measure performance of a department in a way that reflects its contribution to the performance of the total manufacturing process, such as lead time and the total cost of making a product, and it would also be difficult to affect performance against such measures. Consequently performance of current departments is measured in terms of output and efficiency such as standard hours produced, overtime, and utilisation of direct labour and machines. These measures encourage maximum productivity from individual resources but they encourage over production with its detrimental effect on cost and lead times, and will discourage stopping production in order to introduce improvements. Increasing accountability for, and making more visible, performance related to customer satisfaction will therefore encourage desirable behaviour, in both, the management of day to day operations and also guiding and encouraging continuous improvement.

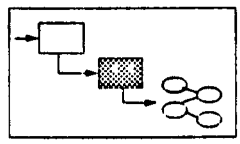
Important Effects of Cellular Manufacturing

Effects of Cellular Manufacturing	*Strong impact on:* *Lead time*	*Cost*
• Reduced WIP and queuing	☑	☑
• Reduced number of operations	☑	☑
• Reduced m/c down time for set ups	☑	☑
• Reduced defects	☑	☑
• Reduced time to isolate and address non-conformance	☑	☑
• Increased accountability for performance	☑	☑
• Increased visibility of performance	☑	☑
• Increased acceptance and use of performance information	☑	☑
• Improved problem solving / Kaisen	☑	☑

Figure 6.2 Output from Stage 1: Important Effects of Cellular Manufacturing

Due to the large number of effects related to lead time and cost, it was decided that only those that had a significant impact on both would be used to determine desirable cellular manufacturing features. This was completed in a single half day session. Figure 6.2 presents the output from stage 1. These effects were rated highly for improving both lead time and cost, and were taken forward to the next stage of concept design for further analysis. In some cases the description of an effect was modified slightly so that it better reflected the company's requirements. Where similar effects were identified, such as reduced WIP and reduced queuing, they were combined so that they did not artificially inflate the importance of their associated features.

Stage 2: Identification of Important Cellular Manufacturing Features



This stage considered the features of cellular manufacturing in light of the current manufacturing system to determine which ones would be most likely to generate the desired effects identified by stage 1 above. Following the procedure described in Chapter 5 and illustrated by Figure 5.4, the project team debated the impact that each of the features would have on the effects to reach an agreement on how each relationship should be scored. This proved to be quite a long arduous task, taking two half day sessions to complete. While the debate was very useful in surfacing opinions and assumptions about how the manufacturing system will be affected by the cellular manufacturing features, the team decided only to identify those relationships that were high impact at this stage. It was felt that any further refinement would be meaningless, given that the aim was to identify a few most significant features, and that the importance of effects determined in the previous stage resulted in an equally coarse classification with all the desired effects being of equal importance. The matrix generated from this analysis is presented in Figure 6.3.

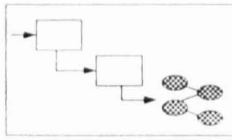
The features that clearly stood out from the general set as the most important for achieving the desired effects were:

Possible Cellular Manufacturing Features \ Desired Effects of Cellular Manufacturing	Red'd WIP / Queueing	Red'd number of operations	Red'd m/c down time for setting	Red'd defects	Red'd time to isolate & address non conformance	Inc'd accountability for performance	Inc'd visibility of performance	Inc'd acceptance and use of performance info	Improved problem solving / kaisen	
Importance	1	1	1	1	1	1	1	1	1	
Inc'd dedication of resources to similar parts			9	9						18
Inc'd ownership of products	9			9	9	9		9	9	54
Inc'd ownership of resources	9			9	9	9		9	9	54
Inc'd dedication of teams				9		9		9	9	36
Inc'd distribution of support					9	9				18
Inc'd collocation of resources	9			9					9	27
Red'd distance between machines										0
Inc'd definition of physical cell boudary										0
Inc'd point of use storage of raw materials										0
Inc'd point of use storage of tools										0
Inc'd point of use storage of finished products										0
Inc'd multi machine manning										0
Inc'd in-cycle ancillary operations	9	9								18
Inc'd multi-skilling / flexible working	9									9
Inc'd operator material handling	9									9
Inc'd shop floor problem solving	9			9	9	9			9	45
Inc'd job satisfaction				9					9	18
Inc'd use of SMED			9							9
Inc'd number of workers capable of setting			9	.						9
Inc'd use of simple small duplicate machines	9		9							18
Inc'd standardisation of tooling										0
Inc'd customisation of handling devices										0
Inc'd devolution of maintenance responsibilities									9	9
Inc'd TPM / preventitive maintenance				9		.			9	18
Improved housekeeping	9		9							18
Inc'd operator responsibility for housekeeping										0
Red'd number of job grades										0
Inc'd rewards for knowledge /skills										0
Red'd piece rate rewards										0
Inc'd team based rewards										0
Pay bonus on complete products only										0
Inc'd gain share / profit share										0
Inc'd dedicated training time			9	9					9	27
Inc'd devolution of training responsibility						9				9
Inc'd flatness of management organisation						9				9
Inc'd use of concensus based management						9				9
Inc'd devolution of scheduling	9					9				18
Inc'd simplification of planning and control										0
Inc'd use of visual systems	9						9			18
Inc'd use of pull control / local WIP regulation	9					9	9			27
Single cycle ordering										0
Red'd batch sizes	9									9
Inc'd devolution of inspection responsibility	9	9				9			9	36
Inc'd inspection throughout process										0
Inc'd use of Poka Yoke										0
Inc'd devolution of PM responsibility								9	9	18
Inc'd publication of results	9		9	9			9	9	9	54
Inc'd link between PMs & customer satisfaction	9		9	8			9	9	9	54
Inc'd & earlier involvement of manuf' in design		9							9	18
Inc'd direct delivery to point of use	9	9								18
Inc'd direct ordering of supplys by user	9					9				18
Inc'd matching of production rate to demand										0
Inc'd direct contact with customer									9	9

Figure 6.3 Matrix Relating Cellular Manufacturing Features to Their Effects

- Ownership of the product and resources.
- Dedicated team.
- Operator inspection.
- Measures of cell performance related to customer satisfaction and results published.

Stage 3: Determination of Supplementary Support Features Required and Presentation of the Concept Design



Having identified the primary features required, each one was then analysed to determine if any further features were necessary to enable the introduction of the primary features. Much of this information had been debated in the previous stage, so it was relatively easy for the project team to brainstorm the support features needed, using a fishbone diagram to structure the output. The results from this process are presented in Figure 6.4 and below.

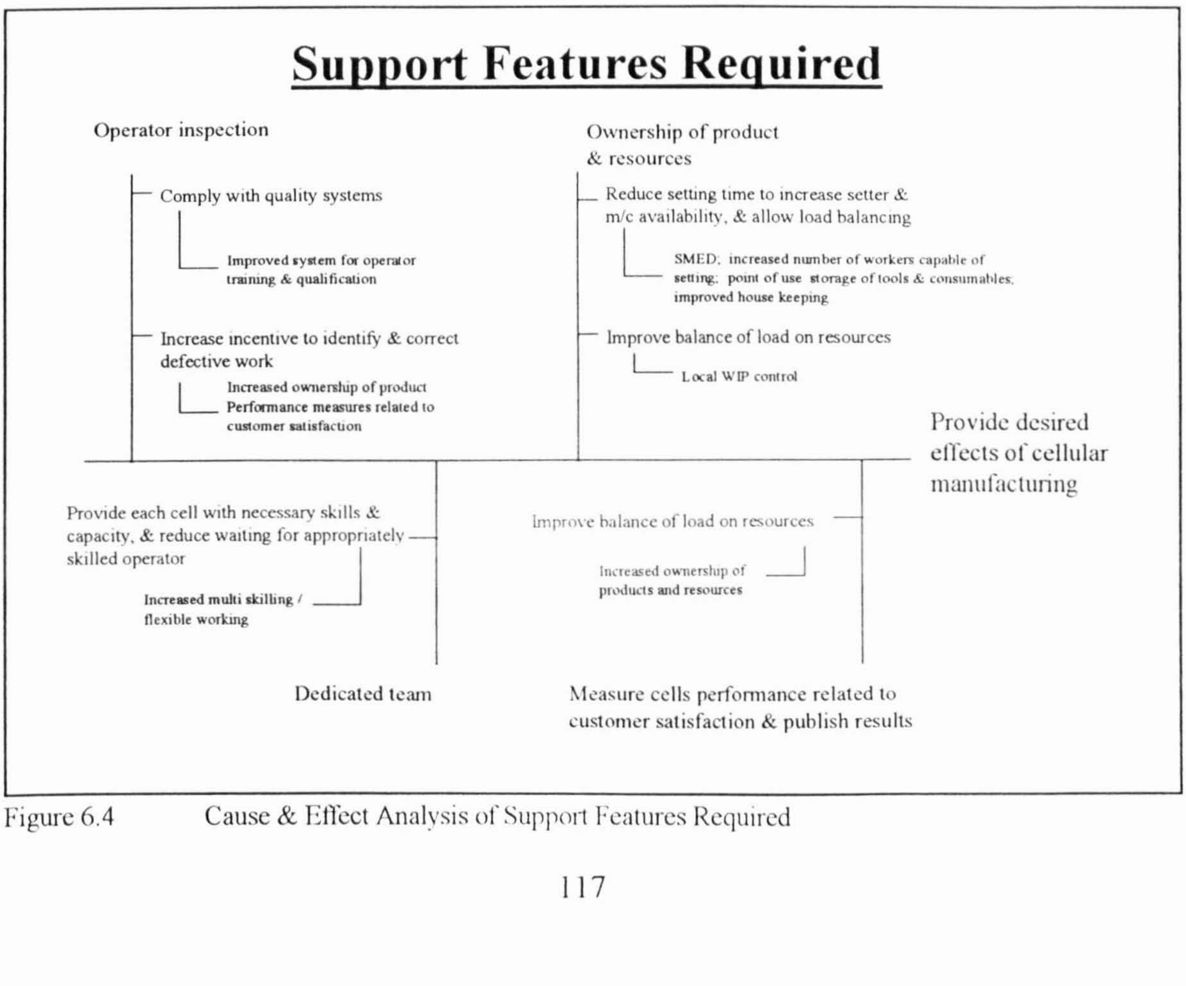


Figure 6.4 Cause & Effect Analysis of Support Features Required

Having determined all the features that are critical for achieving the desired effects, either for their direct influence or for their support of such features, they were then arranged as a network to show the precedencies between them. Figure 6.5 shows the network developed for the case. The arrows indicate the direction of dependence. For example, increased multi-skilling and flexible working will facilitate the dedication of personnel to cells. The double arrows indicate that the two features are mutually supportive. The fishbone diagram and associated network were developed from the insight into the relationships between features generated by the debate in the previous stage of the method. Stage 3 was completed in a single half day session.

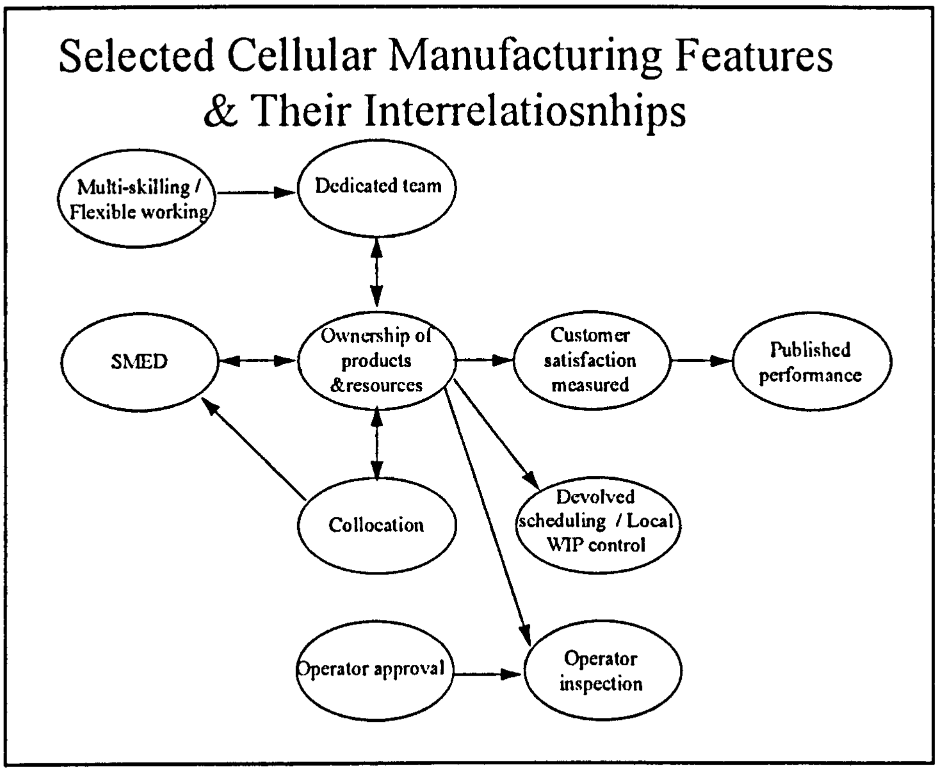


Figure 6.5 Network Diagram of Selected CM Features

6.4 Results and Reflections on the Design Process

The concept design has been accepted by the company management and the project has since proceeded through detailed design and into the early stages of implementation. The company is fully committed to cellular manufacturing, and Cranfield's contract has been extended to support implementation and future development of the cells. The disruption of moving machines caused an initial drop in output of approximately 50%. However, with a month output began to increase again and within two months had surpassed the pre-move production rate. Progress is being made in improving performance, and while overall figures are not yet particularly impressive, some local examples of the benefits of the cellular organisation have been observed already by company managers:

> A foreman noticed that close proximity of processes such as dressing and electro-discharge machining has improved feedback between the operations providing EDM with clearer understanding of the machined profile required by the dressing operation, and leading to a reduction in defects.
>
> The production control manager has found that ownership and collocation has enabled local scheduling to take place between some capacity critical processes, in order to improve the flow of material through the factory. Operators are loading jobs, and in some cases expediting work from previous processes so that they can meet the requirements of subsequent processes.

These benefits confirm the indications provided by the concept design that it would be important to create cells with a high level of ownership. The importance of ownership stressed in the concept design had a significant influence on the process of part machine grouping. First, it helped their management to understand why the "process based cells" they had envisaged prior to Cranfield's intervention would not provide the desired performance improvements. Second, it supported the use of Production Flow Analysis, which besides having a more extensive practical track record than many other procedures, is a manual procedure which advocates intervention by the designer to modify routings in order to eliminate out-of-cell operations. The rest of this section appraises the new approach for designing cellular manufacturing systems against the specified requirements for an improved method.

6.4.1 General Model of Cellular Manufacturing: System Wide Features and Effects

Defining cellular manufacturing as the general set of mutually compatible system wide features and their effects associated with the support and exploitation of semiautonomous product focus groupings of production resources was accepted by all the interviewees involved in appraising the process. It was considered to be a useful way of making an otherwise abstract concept tangible. Compilation and maintenance of a current list of features and effects was perceived to encourage companies to take an external perspective and to provide a common understanding and a useful checklist. The list was however described as daunting by one person, who suggested improving the presentation. Ideas included keeping all the elements on one sheet of paper and using colour codes to highlight common themes. It also became clear in use, that while presenting the concept is more logically grouped by features then effects, when using the model most of the search was for the features associated with a desired effect.

The system wide general model of cellular manufacturing drew attention to the range of changes beyond a new layout that would be needed to make cellular manufacturing successful. Being aware of this in advance prevented the benefits of cellular manufacturing from being delayed, and helped to reduce the difficulties encountered in the early stages of the project when there was still significant cynicism of the cellular manufacturing from some parties within the company. However, the large number of features in the model also raised the problem of what to do first. An explicit concept design stage in the design process allowed the project team to identify appropriate priorities for the introduction of cellular manufacturing.

6.4.2 Tailored Approach

It was unanimously agreed that all situations were different and that some features or techniques would be more or less appropriate in some circumstances than others. Not accounting for this was risking wasted effort and poor results. The consultants in particular, pointed out that sustaining a major programme of change is difficult. The drivers behind such a change must therefore be significant to the business. They also felt that tailoring the nature of the concept to a given situation was an essential part of engendering ownership and commitment to the change.

One proviso was raised. The concept should not be so flexible that anything goes. Some basic principles of cellular manufacturing must be at the core of any implementation. The model and the design process were criticized for not making this clear.

6.4.3 Iterative Approach

Most responses concerned with iteration, suggested that as clear a vision of end point as possible was desirable, but agreed that for a change as significant and company specific as cellular manufacturing, no more than a general outline would be possible. Therefore iteration was desirable to allow the inclusion of new understanding as it develops. The manufacturing director also made it clear that the company could only cope with so much change at once, and that iteration in the medium term was essential. A consultant added that making the iterative nature of the design clear upfront prevents fixed end points being assumed for the design and therefore reduces the change of stagnation.

6.4.4 Concept Design Procedure

Stage 1

The selection of important effects was a valuable intermediate stage in the identification of an appropriate sub set of cellular manufacturing features from the general model, because it made clear the basis for selecting particular features. For example, there was initially a significant misconception within the company as to the function of collocation in cellular manufacturing. The belief that this feature was primarily concerned with reducing transport times diminished the perception of its importance: it was apparent that moving work between queues more quickly would not have much of an effect on lead time. However, linking collocation with ownership, visibility, and communication rectified this situation. Consequently, greater effort was made to collocate processes than would have been the case.

The consultants asked to comment on the method, suggested that in decomposing the problem into a logical sequence of cause and effect the method allows a wider involvement in the planning process and supports an appropriate relationship between "experts" and managers. Exposition of a reasoned argument was also considered to help obtain commitment to the design.

The matrix was found to be easy to understand, and provided an appropriate logic and mechanism for identifying important effects. It took performance improvement objectives into account along with the potential impact of the effects on the current manufacturing system. The large number of effects in the general model of cellular manufacturing required that a vigorous selection procedure was used to isolate the most critical effects. This was achieved by only considering the two most important strategic objectives. This also simplified the application of the matrix procedure as it became possible just to identify those effects that were considered to be significant to both objectives. It was pointed out that the matrix procedure assumes a certain level of knowledge, and that it was likely to need a skilled facilitator in many cases.

Stage 2

The matrix was also considered to provide the appropriate logic for the identification of important features. The scoring system was simplified at this stage as well. This was partly because the simplified scoring procedure used to determine important effects meant that those selected were all of approximately equal significance. Also, as the aim of the procedure is to determine those features that will have the greatest impact on performance there was little point in using an elaborate scoring system at this stage. In practice, it was considered sufficient to identify strong relationships between features and effects. The relative significance of a feature is indicated by the number of effects it is related to.

Again the matrix approach was considered to be helpful in allowing wider participation in the design process, and similar concerns were expressed by the consultants about the need for facilitation to ensure a successful result. The stage two matrix took twice as long to complete as stage one. It was suggested that advanced briefing of the selected participants would smooth the running of the process. The general model of cellular manufacturing is compiled from many specific explanations of features and their effects, and consequently it is possible to identify several similar effects as being important. This would obviously bias any computation relating features to these effects. In this case, the problem was overcome by editing the set of important effects identified before they were imported into the matrix to determine critical features, reducing the repeatability and precision of the procedure. Another option would be to refine the general model so that such duplications were eliminated.

The general opinion was that the advantages outweighed the difficulties associated with the technique. A consultant expressed the view that, as with techniques such as IDEF, Goal Directed Project Planning, and Quality Function Deployment, most value was derived from taking part in the process and the achievement of consensus about a set of decisions, rather than in the details of the solution developed.

Stage 3

Separating the selection of primary features from the selection of support features was useful because it clarified the value of support features and helped to make sure that primary features could be implemented effectively. Some examples are given below:

> Stage 3 drew attention to the company's need to increase multi-skilling, (in particular, cross training of setters and increasing the number of operators competent at setting) in advance of the reorganisation to cells. The fact that the company experienced some difficulties because they were not able to respond adequately to this requirement before they were forced to move machines indicates the value of such insight.

Set-up reduction was also highlighted as a prerequisite to reorganisation. The SMED analysis revealed a large number of opportunities to reduces set-up times. Some of the solutions generated could be implemented immediately, but it was discovered that the cellular organisation was necessary to provide visibility of progress to enable adequate set-up preparation. Point of use storage of tools and pre-loading of pareto CNC programmes require that a clear relationship between part and machine exists. However, advanced knowledge of the options for set-up reduction, meant they could be implemented rapidly after the reorganisation to cells. It also provided guidance and constraints to the design of other manufacturing system elements such as, layout, management of tooling, visible control, performance measurement, and operator inspection.

Stage 3 also highlighted the interdependence of ownership, dedicated teams, and collocation. It was clear therefore that the detailed design of these features would need to be developed in conjunction with one another, and that all three elements would need to be implemented simultaneously.

The network diagram was considered to be appropriate for presenting the interrelationships between cellular manufacturing features, providing a foundation from which could be developed, for example, into a Gantt chart to support the planning of detailed design and implementation. It was suggested however, that there was more than one purpose to the presentation of the concept design, including the broader communication of a vision and to seek justification for the change. The first could be improved by generating a pictorial representation of the features and effects. The second would require a more explicit presentation of performance improvement expectations.

The overriding conclusion from the process participants involved in the industrial case was that the concept design procedure has been valuable in helping the company identify a coherent set of cellular manufacturing features that are critical to achieving their desired performance improvements. The opinion of those with a broader perspective of the problem of designing cellular manufacturing systems, was that the approach provided a useful way of perceiving the cellular manufacturing concept and the design process, that was by its nature, generally applicable. It was suggested by one consultant that it made explicit the approach that he would adopt intuitively. The concept design procedure was considered to appropriate logic for structuring the decisions associated with developing a tailored cellular manufacturing concept.

6.5 Conclusions

A novel approach to the design of cellular manufacturing systems has been tested in an industrial situation and against the experience of consultants and industrialists. The test has provided evidence to support the validity of the system wide model of cellular manufacturing, the iterative design process (incorporating a concept design stage for tailoring the general concept of cellular manufacturing to a specific situation), and the concept design procedure.

The model of cellular manufacturing as a general set of associated system wide features was accepted and found to be a useful communication aid and check list. The range of features identified as being critical to the company's desired performance improvements is compatible with a system wide concept of cellular manufacturing.

There was unanimous approval for a tailored approach to the introduction of cellular manufacturing. The fact that some features were identified as being critical to the company's desired performance improvement, while others were considered to be insignificant, gave further credibility to this approach.

It was confirmed that an iterative design process was an appropriate practical response to the complexity of a manufacturing system, the scale of the change involved in introducing cellular manufacturing, the flexibility of the cellular manufacturing concept and the potential for environmental changes over time.

The concept design stage was performed successfully and provided useful insights that were considered to have improved the design of the cellular manufacturing system.

- Explicit statement of overall company performance improvement objectives provided a common understanding upon which to base design decisions and an integrating effect on the design of the various elements of the manufacturing system.

- The matrix procedure for supporting concept design was used successfully to help identify the relative importance of cellular manufacturing features and their effects to achieving the company's performance improvement objectives.

- The matrix procedure was found to be sufficiently straightforward that all levels of the organisation could participate in its construction. The Stage 2 matrix was time consuming to construct but the insight developed and communicated by participating in this process was considered to more than justify the time spent.

- Identification of support features was shown to be a valuable aspect of the concept design procedure, as several support features were identified as being required to enable the primary features selected. It was felt that this helped reduce the potential for negative effects in the early stages of the change that would have delayed benefits and could have undermined the project before the value of cellular manufacturing had been demonstrated.

Concept design proved to be an important stage in the process of developing a cellular manufacturing system in this case, helping to focus attention on those features that provided the greatest improvements to the performance of their current system according to their strategic objectives. The process also increased the company's understanding of cellular manufacturing principles and techniques, and the mechanisms by which they improve performance. This helped their personnel contribute more effectively to the detailed design of the various elements of the manufacturing system, and is expected to reduce the chances of the design being corrupted during implementation. It also means the company will be better equipped to develop the design to meet future requirements. The concept design is in the process of being developed into detail plans and implemented. Initial feedback from the new cellular manufacturing system is encouraging, and significant performance improvements are anticipated in the future.

The evidence provided by industrialists, academics, and consultants suggests that the novel approach for designing cellular manufacturing system developed by this research, is suitable for wider application than just to the specific circumstances in which it was tested.

Chapter 7 Discussion and Conclusions

This chapter discusses and concludes the findings of this research. The issues raised by the review of the theory and practice of cellular manufacturing and the design of cellular manufacturing systems, and by the development and testing of a novel approach to the design of cellular manufacturing systems, are compared with the research problem and aims submitted by this thesis. The research process and the limitations of the findings are discussed, and further opportunities for research arising from this work are identified.

7.1 Introduction

The problem undertaken by this research was how to provide a system wide concept of cellular manufacturing and support the design of a cellular manufacturing system based on this concept. The research aims developed to address this problem are given below.

i. Develop a system wide definition of cellular manufacturing that provides a useful reference to guide the design of cellular manufacturing systems.
ii. Identify the strengths and weaknesses of current approaches to the design of cellular manufacturing systems.
iii. Determine the requirements for an improved approach to the design of cellular manufacturing systems.
iv. Develop a practical method for designing cellular manufacturing systems that satisfies the requirements defined by iii. above.
v. Test and refine the method through practical application.

The nature of cellular manufacturing and the problem of designing cellular manufacturing systems have been explored and a new model has been proposed. Existing methods for designing cellular manufacturing systems have been reviewed and their short comings have been identified. An improved design process, building on the new model of cellular manufacturing has been specified and developed to undertake the design of a cellular manufacturing system. Concept design was highlighted as an important but neglected stage in the design of cellular manufacturing systems. A procedure was developed for tailoring the general concept of cellular manufacturing to a company's specific objectives and circumstances. The new approach to designing cellular manufacturing systems has been tested by using it in a real industrial case and it has also been assessed by experienced independent designers of cellular manufacturing systems. The following discussion will compare the results of this research with the research aims submitted.

7.2 Develop a System Wide Definition of Cellular Manufacturing

The purpose of clarifying the definition of cellular manufacturing was to determine the task of designing a cellular manufacturing system, and to provide a useful reference for this. The nature of cellular manufacturing has been explored by reviewing its historical development into current theory and practice.

> *Cellular manufacturing is an important approach to the organisation of production with the potential to provide significant improvements in performance over traditional organisations.*

This research supports the view that cellular manufacturing is a system wide concept and that it is also a flexible concept. These characteristics have been incorporated into a novel definition of cellular manufacturing. The model has been substantiated by the compilation of a wide range of cellular manufacturing system features and their desired effects from the review of theory and practice. Evidence to support the validity of the model was generated by this research and is discussed in section 7.6.

Cellular manufacturing is defined in this thesis as a general set of mutually compatible production system wide features for supporting or exploiting self contained groupings of manufacturing resources. This model is applied to a particular situation by selecting the appropriate subset of features for the specific objectives and constraints of that situation.

The nature of cellular manufacturing as defined above makes for a difficult design task. The task is further compounded by the complexity of manufacturing systems, and the poorly defined relationships between cellular manufacturing features and performance.

7.3 Identify the Strengths and Weaknesses of Current Methods for Designing Cellular Manufacturing Systems

A review of the theory and practice of designing cellular manufacturing systems revealed that the majority of methods were concerned with part machine grouping. These undertake an essential task in the design of a cellular manufacturing system, however, the scope of the design problem addressed by these methods is inadequate. Moreover, the restricted focus of research in this area has resulted in the development of many procedures that are not actually capable of tackling real industrial problems.

There is a small number of methods that consider the broader impact of cellular manufacturing on the production system. None of these were adequate for the task of designing a cellular manufacturing system based on flexible general model developed by this research. All the methods reviewed were associated with one or more of the following shortcomings:

- Are based on a fixed and restricted concept of what features comprise cellular manufacturing, and assume a fixed sequence of introduction is suited to all cases.
- Provide no guidance as to what principles or manufacturing system features should

be considered for the introduction of cellular manufacturing.

- Neglect aspects of the production system.
- Do not link the design of cellular manufacturing system features to strategic performance improvement objectives.
- Do not address the complexity of manufacturing systems. Do not tackle the interrelationships between design decisions.

None of the methods reviewed addressed the tailoring of general model of cellular manufacturing to a specific situation.

It is concluded that a new, improved approach to the design of cellular manufacturing systems, which builds upon the new model of cellular manufacturing, is required.

7.4 Determine Requirements for an Improved Approach to the Design of Cellular Manufacturing Systems

The issues raised by reviewing the nature of cellular manufacturing and the existing methods for designing cellular manufacturing systems above, were used to specify and develop a new improved design process.

The primary requirement for an improved approach is that it should capable of putting into operation the flexible general model of cellular manufacturing defined by this research.

The auxiliary requirements determined to be necessary to satisfy the primary requirement are as follows:

- *An improved approach must address the full extent of the manufacturing system affected by the cellular manufacturing concept.*

- *An improved approach must contain a stage and procedure for tailoring the general model to the specific circumstances and objectives.*

In order to be effective, an improved approach would also have to recognise the complex interrelationships between production system elements and help the designer to comprehend the impact of cellular manufacturing features on the performance of the production system, despite being reliant on weak and conflicting theories. Section 7.5 describes the new process for designing cellular manufacturing systems developed to satisfy these requirements.

7.5 Develop a Practical Method for Designing Cellular Manufacturing Systems Based on the Specified Requirements

> *A novel approach to designing cellular manufacturing systems has been developed that incorporates an explicit concept design stage for tailoring the flexible general model of cellular manufacturing to specific circumstances and objectives.*

Concept design addresses the primary requirement defined by this research for an improved approach to the design of cellular manufacturing systems. It also reduces the level of design detail considered to allow a wider range of the production system elements to be considered together. In this way it helps to address the complexity of manufacturing systems design.

By starting with a comprehensive system wide model based on the theory and practice of cellular manufacturing, and paring this back to those elements that are critical to the specific manufacturing system in question, the process avoids the criticism that it pays insufficient attention to any particular aspect of the manufacturing system.

The design process is iterative to help to cope with the complexity of the manufacturing system, the ramifications of cellular manufacturing features, and the poorly defined relationships between cellular manufacturing features and performance. Iteration also allows the process to account for changes in the objectives and constraints imposed upon the system, encourages continuous improvement and allows for development of the cellular manufacturing concept.

> *Concept design has been identified as an important but neglected stage in the design of cellular manufacturing systems.*

As a consequence, this research has focused on the development of a procedure to support the concept design stage of the process defined above. The main difficulties with this task are associated with understanding the impact of cellular manufacturing features on performance. The is impeded by the complex nature of cellular manufacturing and the competing theories, which result in poorly defined relationships.

> *A matrix based procedure has been developed to relate the features of the general case of cellular manufacturing, through their effects on the existing production system, to strategic performance improvements. The matrix procedure provides a framework for determining the relative importance of the cellular manufacturing features to achieving the company's desired performance improvements.*

Validation of the new, improved approach to designing cellular manufacturing systems, and its concept design procedure, is described in sections 7.6 and 7.7 below

7.6 Test and Refine the Method Through Practical Application

The extent to which the new approach to designing cellular manufacturing systems satisfies the requirements specified, and the practical value of this method were tested in an industrial case study, and against the experience and opinion of industrialists, academics and consultants.

A system wide approach is necessary and has been provided by the method developed.

This research has provided evidence to support the flexible system wide model:

- All the features contained in the model have been associated with the theory and practice of cellular manufacturing.
- Not all the features are associated with every application of cellular manufacturing.
- The industrial case study identified a coherent subset of production system features from this model as being critical to achieve the company's desired performance improvements.
- The model was accepted by experienced industrialists, academics and consultants.

The case confirmed that a systems wide approach was important because the company agreed that simply reorganising the machines and people would not provide substantial benefits and that the additional system elements identified were significant inhibiters to improved performance. The concept design developed in the case identified a range of manufacturing system elements, from skill levels and facilities layout to set-up procedures and performance measurement, as being important. It is of course possible that these features could have been identified without using the improved process. However, this approach has provided a systematic method to make sure that all features of cellular manufacturing are considered, so that the only features that were not included in the concept design were those that have been deliberately excluded.

It is necessary to have a tailored approach to the design of cellular manufacturing systems, and has been provided by the method developed.

The fact that a coherent subset of the features contained in the general model of cellular manufacturing were identified as being critical to the case situation, while others were considered to be insignificant supports that view that cellular manufacturing is a flexible concept. A tailored approach to the design of cellular manufacturing systems saves effort from being wasted, or worse performance from deteriorating as a result of introducing features that are inappropriate to a specific situation. The review of the design process in the industrial case suggested that the method has helped to identify an appropriate subset of cellular manufacturing features, enabling the company to focus limited resources on introducing those features that would give the most benefits. While the selected benefits may have been identified without using the method defined by this research, the new approach has provided a systematic and structured way to identify the relative importance of cellular manufacturing features to achieving the company's desired performance improvements.

The ability to address the complex impact of cellular manufacturing on the production system despite the ill-defined relationships between cellular manufacturing features and performance, is important and has been provided for by the method developed.

Complexity, and poorly defined relationships between cellular manufacturing features and performance are addressed in the new method by four key aspects of the new method.

- An explicit concept design stage, where the interaction between design features can be considered.
- Iteration, to allow the design to accommodate the new insights generated as the concept is developed and applied to a specific situation.
- A novel matrix procedure that can utilise subjective data, and facilitates the organisation of knowledge from multiple sources.
- An explicit stage for determining the support requirements of those features that had been identified as having a significant impact on performance.

The fact that support features were identified in the industrial case and were considered to be important by the company supports both the notion that identifying interrelationships will improve the cellular manufacturing system design and also that the proposed process has been successful in encouraging this action. Making important interrelationships explicit was also found to have several benefits for communicating the design in practice. First it helped to justify the need for features that would not have a large direct impact on performance. It was also necessary to convince people that it was feasible to introduce some of the primary features.

The new approach to cellular manufacturing has been successfully tested in an industrial case and against the experience and opinions of industrialists, academics, and consultants.

> *It is concluded that the new method for designing cellular manufacturing systems, developed by this research meets the criteria specified as requirements for an improved approach.*

7.7 Limitations of the Research

Any research design will have limitations which should be taken into account when interpreting the results. The main limitations arising from the approach used in this research are discussed below.

The primary requirement of this research was that it should investigate and address the practical problem of designing cellular manufacturing systems. Therefore, a research programme was developed that incorporated close contact with industry. A wide range of contacts were maintained during the problem definition, so that the problem identified would be more generally applicable than to one manufacturing system.

However, the desire to test the improved method for designing cellular manufacturing systems by applying it in a real industrial project gave rise to two major problems. First, time constraints meant that testing would be restricted to a single case. Second, the author's involvement in the case could effect the operation and effectiveness of the method being tested. Assessment of the method by cellular manufacturing system designers that were either not connected with the industrial case study, or had a greater breadth of experience against which to judge the method, was undertaken to increase the external validity of the research. This also provides additional sources of evidence, to triangulate with the case evidence in order to improve confidence in the findings.

The method was applied in a specific company operating within a particular environment, and has therefore only been validated for similar circumstances (eg. batch production, discrete part, complex precision machining). However, the general model has been developed from a broad base of information relating to a wide range of industries. The process itself does not have any particularly industry specific characteristics and has been deliberately developed for the purpose of tailoring a general model to a specific situation. The process should therefore be applicable for designing cellular manufacturing systems in many production environments. Support for this view was provided by the positive assessments of the method's general value made by experienced cellular manufacturing system designers.

The case used to test the method, involved a company with no experience of cellular manufacturing, that was attempting to take its first steps in this direction. While the process is intended to be iterative the limit of its utility are not known. Only one major iteration of the process was undertaken in the industrial case. Although this limits the extent to which the defined process has been validated by practical application, sufficient confidence has been developed in the process from the initial iteration, that at the time of writing, the cell design team are using the process to define the next stages of development of the company's cellular manufacturing system.

7.8 Opportunities for Further Work

This research has developed a method for tailoring a general system wide concept to the requirements of a specific manufacturing system. Further research to develop and refine the general conceptual model of cellular manufacturing would greatly assist the design of cellular manufacturing systems. Improvements in the structure of the model, the definition of relationships between the various features and effects of cellular manufacturing, and presentation of the model would be valuable.

Although this research has focused on concept design, by advocating an iterative process recognises the importance of the interaction between design and implementation. However, this relationship was not explored in detail, and implementation is in general, under researched. A comprehensive process would need to provide guide lines for implementation.

The method could be developed and refined by feedback from further usage. Of particular importance would be the pursuit of the evolution of a cellular manufacturing system through more iterations of the process and using it to support projects in different manufacturing environments. Evaluating the use of the method without the author's involvement would add to the confidence in the validity of the research. There is also scope for testing various approaches for applying the method, such as, with and without facilitation, or with various degrees of worker participation.

Development of an appropriate delivery methodology and support tools would be useful. For example, a work book may be helpful to guide the user through the method, and a computer tool, such as a formatted spreadsheet, would minimise the task of constructing the matrices, and recording the design decisions.

The method appears to be suited to the application of other manufacturing systems concepts that have similar attributes to cellular manufacturing. Characteristics that would suggest this approach might be suitable include, system wide complex effects, ill defined theory, described as collections of tools, techniques or features. Examples of manufacturing systems concepts that exhibit some these characteristics are just-in-time, concurrent engineering, and total quality management. Determining the applicability of the method to other domains would be an interesting avenue for further research.

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Appendix A

Feature / Effects Definition of Cellular Manufacturing

Features	Effects
Function: Make Product Organisation: Resources dedicated to certain similar parts *(Fry, Wilson & Breen 1987; Noaker 1993)* Ownership of product *(Fry, Wilson & Breen 1987)* Ownership of resources *(Morton et al 1993)* Dedicated team *(Burbidge 1989; Prickett 1993)* Devolved indirect tasks *(See later features)*	Reduced processing variables *(Noaker 1993)* Increased consistency of production *(Fry, Wilson & Breen 1987)* Reduced scrap *(Fry, Wilson & Breen 1987; Morton et al 1993)* Improved accountability for cost, quality & delivery *(Burbidge, Partridge & Aitchison 1991; McManus 1991)* Enabled delegated decision making *(Burbidge, Partridge & Aitchison 1991)* Improved foundation for evolutionary development of automation *(Burbidge, Partridge & Aitchison 1991)* Reduced number of set ups necessary *(Dumolien & Santen 1991)* Reduced set up times *(Fry, Wilson & Breen 1987; Kellock 1992; Welke & Overbeke 1988)* Increased perception of task significance*(Huber & Hyer 1985)* Improved morale & satisfaction *(Burbidge, Partridge & Aitchison 1991; Fry, Wilson & Breen 1987; Greene & Sadowski 1984)* Increased part familiarity/expertise & reduced start ups *(Fry, Wilson & Breen 1987; McManus 1991)* Enabled problem solving *(Nimmons, Williams & Cursham 1995)* Simplified material flow *(Williams 1991)* Reduced information / documentation requirements *(Masom 1993; Williams 1991)* Enabled simplified production planning & control *(Masom 1993; Nimmons, Williams & Cursham; Schonberger)* Reduced expiditing/WIP tracking *(Greene & Sadowski 1984; McManus 1991)* Enabled maintenance planning *(Morton et al 1993)* Reduced process planning effort *(Dumolien & Santen 1991; Mosier & Taube 1985)* Increased standardisation of job times *(Dumolien & Santen 1991)* Enabled simplified cost accounting *(Schonberger 1986)* Improved cost estimating *(Dumolien & Santen 1991)*
Distributed support *(Kellock 1992)*	Increase cell autonomy *(Kellock 1992)* Timely implementation of shopfloor improvement suggestions *(Stoner, Tice & Ashton 1989)*

Layout Collocation of product's process requirements *(Burbidge, Partridge & Aitchison 1991)* Minimum distances between processes / machines *(Fry, Wilson & Breen 1987; Nimmons, Williams & Cursham 1995)* Defined physical boundary *(Burbidge 1989; Prickett1993)*	Improved communication/feedback *(Huber & Hyer 1985; Schonberger 1986)* Improved problem solving *(Schonberger 1986)* Enabled low WIP *(Schonberger 1983)* Reduced material handling *(Fry, Wilson & Breen 1987; Greene & Sadowski 1984)* Reduced damage *(Nimmons, Williams & Cursham 1995; Stoner, Tice & Ashton 1989)* Increased team & territory definition *(Burbidge 1989)* Improved visible control *(Prickett 1993)*
Cell storage of raw materials, tools, finished products *(Deeming 1993; Morton et al 1993; Stoner, Tice & Ashton 1989)*	Reduced setup times *(Morton et al 1993)* Reduced handling *(Greene & Sadowski 1984)* Increased visibility of requirements *(Stoner, Tice & Ashton 1989)* Reduced WIP *(Stoner, Tice & Ashton 1989)* Reduced shortages Reduced admin *(Greene & Sadowski 1984)* Reduced storage & retrieval complexity ie. no auto systems needed *(Stoner, Tice & Ashton 1989)*
Job Design Multi machine manning & in cycle ancillary ops *(Burbidge 1988; Schonberger 1983; Stoner, Tice & Ashton 1989)*	Reduced operations *(Schonberger 1983)* Reduced queuing*(Schonberger 1983)* Reduced handling *(Black 1991; Burbidge 1988)* Improved labour efficiencies *(Burbidge 1988)*
Multi-skilling / flexible working*(Burbidge 19988; Deeming 1993; McManus 1991; Noaker 1993)*	Increased flexibility of job assignment *(Burbidge 1988; Noaker 1993)* Reduced WIP *(Fry, Wilson & Breen 1987)* Improved labour efficiency *(Bennett & Forrester 1993)* More tangible relationship between operator tasks & product quality / process performance *(McManus 1991)* Increased employee motivation *(McManus 1991)*
Operator material handling *(Stoner, Tice & Ashton 1989; Welke & Overbeke 1988)*	Reduced queuing & handling *(Welke & Overbeke 1988)*
Shop floor problem solving *(Deeming 1993; Schonberger 1987)*	Reduced defects *(Deeming 1993; Schonberger 1987; Steudel & Desruelle 1992)*
Satisfying work *(Huber & Brown 1991)*	Reduced absenteeism *(Deeming 1993; Huber & Brown)* Reduced labour turnover *(Huber & Brown)* Improved labour productivity *(Bennett & Forrester 1993)*
Setting: SMED *(Black 1991; Morton et al 1993)* All workers capable of setting (*Morton et al 1993)*	Reduced set up times *(Black 1991; Morton et al 1993)* Reduced waiting time *(Morton et al 1993)*
Mechanisms Facilities management: Duplicates of simple / small machines *(Schonberger 1983; Stoner, Tice & Ashton 1989)*	Reduced number of set ups *(Stoner, Tice & Ashton 1989)* Reduced impact of breakdowns *(Stoner, Tice & Ashton 1989)* Increased flexibility for redefining the cells / process *(Schonberger 1986; Stoner, Tice & Ashton 1989)* Reduced investment in new machines *(Schonberger 1983, 1987; Stoner, Tice & Ashton 1989)* Increased opportunity for in-cycle operations *(Schonberger 1983, 1987; Stoner, Tice & Ashton 1989)*

Standardised tooling *(Morton et al 1993; Noaker 1993)*	Reduced number of tools *(Jackson 1978; Noaker 1993)* Reduced set up times *(Morton et al 1993)*
Customised handling devices *(Omand 1992; Welke & Overbeke 1988)*	Reduced damage *(Omand 1992)* Improved health & safety *()*
Maintenance: Devolved maintenance *(Noaker 1993; Stoner, Tice & Ashton 1989)*	Increased resource for routine maintenance *(Stoner, Tice & Ashton 1989)* In cycle maintenance enabled *(Schonberger 1986)* Increased morale *(Stoner, Tice & Ashton 1989)* Increased ownership *(Morton et al 1993)* Reduced unplanned downtime *(Noaker 1993; Stoner, Tice & Ashton 1989)* Improved maintenance scheduling *(Morton* et al 1993)
Total Productive Maintenance *(Morton et al 1993)* Preventative maintenance *(Stoner, Tice & Ashton 1989; Welke & Overbeeke 1988)*	Maximise machine availability *(Morton et al 1993; Welke & Overbeeke 1988)* Reduced unplanned delays *(Morton et al 1993; Stoner, Tice & Ashton 1989)* Enabled low WIP *(Schonberger 1983)*
Good housekeeping *(Masom 1993; Morton et al 1993)* Operator responsibility for housekeeping *(Black 1991)*	Improved quality workmanship *(Masom 1993)* Increased marketing opportunities *(Masom 1993)* Improved industrial relations *(Masom 1993)* Improved maintenance *(Morton et al 1993)* Improved safety *(Black 1991)* Visual control and reduced unnecessary motions and searching by operators *(Black 1991; Schonberger 1986)*
Human Resource Management: Reduced job grades *(Peters 1989)* Pay for knowledge / skills *(Huber & Brown 1991; Peters1989; Schonberger 1986)* Stable income plan / straight day work / monthly salary *(Burbidge 1979; Schonberger 1986; Stevens 1987)* Team based rewards *(Welke & Overbeeke 1988)* Pay bonuses on completed products only *(Prickett 1994)* Gain share / Profit share *(Huber & Brown 1991)*	Encourage multiskilling *(Huber & Brown 1991; Peters1989; Schonberger 1986)* Encourage flexible working *(Burbidge 1979)* Reduce admin *(Burbidge 1979)* Discourage overproduction *(Schonberger 1986)* Encourage team working *(Welke & Overbeeke 1988)* Encourage low WIP / fast throughput *(Prickett 1994)* Encourage factory performance improvements *(Huber & Brown 1991)*
Increased (dedicated) training time *(Huber & Brown 1991; McManus 1991; Stevens 1987)* Devolved training responsibility *(Peters1989)*	Increased employee motivation *(McManus 1991)* Increased multiskilling *(McManus 1991)* Improve interpersonal & group working skills *(Huber & Brown 1991)* Improved problem solving skills *(Huber & Brown 1991)* Improved career development options *(Huber & Brown 1991)*
Management and Control Flat management organisation *(Masom 1993; Peters 1989)* Consensus based management *(Buchanan 1994)*	Increased accountability *(Masom 1993)* Increased empowerment for local decisions *(Masom 1993)* Improved industrial relations *(Masom 1993)*

Production Planning and Control: Devolved scheduling *(Fry, Wilson & Breen 1987; Peters 1989; Prickett 1994)* Simplified shop floor production scheduling & control *(Buchanan & Preston in Buchanan 1994; Deeming 1993; Schonberger 1986)* Visual systems *(Stoner, Tice & Ashton 1989)*	Reduced WIP *(Fry, Wilson & Breen 1987; Stoner, Tice & Ashton 1989)* Increased visibility of plans & progress *(Deeming 1993; Kellock 1992; Prickett 1994)* Increased opportunity for presetting *(Morton et al 1993)* Increased operator commitment to plan *(Deeming 1993)* Increased operator satisfaction *(Deeming 1993)* Reduced information processing & admin *(Kellock 1992)* Reduced PPC staff *(Masom 1993; Schonberger 1986)* Reduced need for shop floor data collection *(Stoner, Tice & Ashton 1989)* Increased realism of planning & customer promises *(Love & Barekat 1989; Prickett 1993)* Increased speed and timeliness of replanning *(Barekat 1991)*
Pull control / local WIP regulation *(Kellock 1992)* Single cycle ordering *(Burbidge 1989)*	Reduced WIP *(Kellock 1992; Omand 1992)* Reduced load surges *(Burbidge 1989)* Enables sequencing parts with same set up *(Burbidge 1988)*
Low WIP *(Stoner Tice & Ashton 1989)*	Reduced space *(Kumar & Hadjinicola 1992; Masom 1993; Schonberger 1983)* Reduced WIP tracking & admin *(Greene & Sadowski 1984; McManus 1991)* Reduced queue times *(Jackson 1978; Kellock 1992)* Reduced version control & obsolescence *(Burbidge 1989; Deeming 1993; Omand 1994)* Reduced damage *(Jackson 1978)* Reduced handling *(Schonberger 1986)* Reduced PPC & progress *(Schonberger 1986)* Reduced time to identify process errors & isolate defects *(Stoner, Tice & Ashton 1989)* Reduced processing of defective items *(Stoner, Tice & Ashton 1989)* Increased visibility of system problems *(Schonberger 1983; Taheri 1990)* Increased visibility of replacement requirements Improved information for corrective action *(Stoner, Tice & Ashton 1989)*
Small batches (towards single items)*(Kellock 1992; Stoner, Tice & Ashton 1989)*	Reduced WIP *(Stoner, Tice & Ashton 1989)* Reduced time to identify defects *(Stoner, Tice & Ashton 1989)* Reduced number of defects produced *(Stoner, Tice & Ashton 1989)* Reduced time to complete running job*(McManus 1991)* Reduce lumpiness of loads on facilities *(Harrison 1992; Kirton & Brooks 1994)*

Quality: Operator inspection *(Deeming 1993; Fry,Wilson & Breen 1987)* 100% inspection throughout process *(Stoner, Tice & Ashton 1989)* Poke Yoke *(Black 1991)*	Reduced response time *(Fry,Wilson & Breen 1987)* Reduced number of defects *(Fry,Wilson & Breen 1987)* 100% inspection at source enabled *(Stoner, Tice & Ashton 1989)* Reduced time to identify process errors & isolate defects *(Nyman 1992; Stoner, Tice & Ashton 1989)* Reduced processing of defective items *(Dumolien & Santen 1983; Stoner, Tice & Ashton 1989)* Increased visibility of replacement requirements Improved information for corrective action *(McManus 1991; Stoner, Tice & Ashton 1989)* In cycle inspection enabled *(Schonberger 1986)* Reduced inspection cost *(Dumolien & Santen 1991; Schonberger 1986)*
Performance Measurement: Devolved ownership of performance measures *(Peters 1989; Prickett 1994)* Publish results *(Deeming 1993)*	Improved timeliness *(Huber & Brown 1991)* Increased acceptance *(Huber &Brown 1991)* Increased use of information *(Prickett 1994; Schonberger 1986)* Improved feedback & visibility of performance *(Prickett 1994)* Improved job satisfaction *(Prickett 1994)*
Performance measures related to customer satisfaction *(Masom 1993)*	Increase visibility of customer satisfaction *(Masom 1993)* Discourage activities that reduce customer satisfaction *(Masom 1993)*
Process planning: Early involvement of manufacture in design *(Stoner, Tice & Ashton 1989; Welke & Overbeeke 1988)*	Reduced number of tools required / tooling costs *(Prickett 1994; Stoner, Tice & Ashton 1989)* Improved producibility *(Stoner, Tice & Ashton 1989; Welke & Overbeeke 1988)* Reduced material types required *(Prickett 1994)*
Inputs Direct delivery of material to the cell *(Nimmons, Williams & Cursham 1994; Omand 1992)* Cells ordering supplies direct *(Omand 1992)*	Reduced handling & delays *(Nimmons, Williams & Cursham 1994)* Simplified ordering *(Omand 1992)* - Improved responsiveness to cell needs - Reduced admin / overhead
Outputs Production rate matched to customer demand Direct contact with customer (Passmore 1988)	Minimum WIP (Black 1991; Burbidge 1961, 1989; Schonberger 1986; Wemmerlöv 1988) Increased job significance (Passmore 1988)

Appendix B

Survey of Cellular Manufacturing Research Topics: International Journal of Production Research Jan 87-Jul 93

Date	Authors	Title	Topic	
Vol 31 Jul 93	Kapov and Vakharia	Scheduling a Flow-Line Manufacturing Cell: A Tabu Search Approach	PPC	X
Jun 93	Gupta	Design of Cells for a Flexible Environment Considering Alternate Routings	P-M Grouping New Method	X
	Shafer and Rogers	Similarity and Distance Measures for Cellular Manufacturing Pt II An Extension and Comparison	P-M Grouping New Method?	X
	Ruben, Mosier and Mahmoodi	A Comprehensive Analysis of Group Scheduling Heuristics in a Job Shop Cell	PPC	X
	Wu and Salvendy	A Modified Network Approach for the Design of Cellular Manufacturing Systems	P-M Grouping New Method	X
	Balasubramanian and Panneerselvan	Covering Technique Based Algorithm for Machine Grouping to Form Manufacturing Cells	P-M Grouping New Method	✓
May 93	Shafer and Rogers	Similarity and Distance Measures for Cellular Manufacturing	P-M Grouping Review of Methods	X
Apr 93	Irani, Cavalier and Cohen	Virtual Manufacturing Cells: Exploiting Layout Design and Intercell Flows for the Machine Sharing Problem	P-M Grouping New Method	✓
	Chu	Manufacturing Cell Formation by Competitive Learning	P-M Grouping New Method	X
	Dahel and Smith	Designing Flexibility into Cellular Manufacturing Systems	P-M Grouping New Method	X
Mar 93	Lee and Garcia-Diaz	A Network Flow Approach to Solve Clustering Problems in Group Technology	P-M Grouping New Method	X
Feb 93	Vanelli and Hall	An Eigen Vector Solution Methodology for Finding Part-Machine Families	P-M Grouping New Method	X
Jan 93	Ferreila Riberio and Pradin	A Methodology for Cellular Manufacturing Design	P-M Grouping New Method	X
Vol 30 Dec 92	Song and Hitomi	GT Cell Formation for Minimising Intercell Parts Flow	P-M Grouping New Method	X
Nov 92	Kusiak and Cho	Similarity Coefficient Algorithms for Solving the Group Technology Problem	P-M Grouping New Method	X
Oct 92	Chen	A Petri Net Based State-Transition Model for an Operator Cyclic Walking Pattern Development in GT Cells	Operator Scheduling	X

Date	Authors	Title	Topic	
Jul 92	Damodaran, Lashkari and Singh	A Production Planning Model for Cellular Manufacturing Systems with Refixturing Considerations	PPC	X
Jun 92	Rajamani, Singh, and Aneja	A Model for Cell Formation in Manufacturing Systems with Sequence Dependence	P-M Grouping New Method	X
	Yang and Jacobs	Comparison of Make-to-Order Job Shops With Different Machine Layouts and Production Control Systems	P-M Grouping and PPC Compaisons	X
	Kaparthi and Suresh	Machine-Component Cell Formation in Group Technology: A Neural Network Approach	P-M Grouping New Method	X
May 92	Shafer, Kern and Wei	A Mathematical Programming Approach for Dealing with Exceptional Elements in Cellular Manufacturing	P-M Grouping New Method	X
	Geoffrey, Okobaa, Chen, Changchit and Shell	Manufacturing Cell Formation Using a New Intercell Flow Reduction Heuristic	P-M Grouping New Method	X
	Burbidge	Change to Group Technology: Process Organisation is Obsolete	P-M Grouping Method Evaluation	✓
Mar 92	Ketcham	A Branch and Bound Approach to Facility Design for Continuous Flow Manufacturing Systems	P-M Grouping New Method	X
	Logendran	A Model for Duplicating Bottleneck Machines in the Presence of Bugetary Limitations in Cellular Manufacturing	P-M Grouping New Method	X
Jan 92	Tan	A Simulated Annealing Algorithm for Allocating Space to Manufacturing Cells	Layout Planning	X
Vol 29 Dec 91	Moon, Gallego and Simchi-Leui	Controllable Production Rates in a Family Production Context	PPC	X
Nov 91	Frazier and Gaither	Seed Selection Procedures for Cell Formation Heuristics	P-M Grouping New Method	X
Oct 91	Park and Steudel	A Model for Determining Job Throughput Times for Manufacturing Flow Line Work Cells with Finite Buffers	Analytical Model CM System Performance	✓
	Boe and Cheng	A Close Neighbour Algorithm for Designing CM Systems	P-M Grouping New Method	X
Sept 91	Sule	Machine Capacity Planning in Group Technology	P-M Grouping New Method	X
	Mahmoodi and Dooley	A Comparison of Exhaustive and Non-Exhaustive Group Scheduling Heuristics in a Manufacturing Cell	PPC	X
Aug 91	Kern and Wei	The Cost of Eliminating Exceptional Elements in Group Technology Cell Formation	P-M Grouping New Method	X
Jul 91	Chu and Hayya	A Fuzzy Clustering Approach to Manufacturing Cell Formation	P-M Grouping New Method	X

Date	Authors	Title	Topic	
Jun 91	Askin, Cresswell, Goldberg and Vakharia	A Hamiltonian Path Approach to Reordering the Part-Machine Matrix for Cellular Manufacturing	P-M Grouping New Method	X
Mar 91	Srinivasan and Navendran	GRAFICS - A Non-Hierarchical Clustering Algorithm for Group Technology	P-M Grouping New Method	X
Feb 91	Boctor	A Linear Formulation of the Machine-Part Cell Formation Problem	P-M Grouping New Method	X
	Logendran	Impact of Sequence of Operations and Layout of Cells in Cellular Manufacturing	P-M Grouping New Method	X
Vol 28 Dec 90	Nagi, Harhalakis and Proth	Multiple Routings and Capacity Considerations in Group Technology Applications	P-M Grouping New Method	X
Nov 90	Vohra, Chen, Chang and Chen	A Network Approach to Cell Formation in Cellular Manufacturing	P-M Grouping New Method	X
Sep 90	Franks, Loftus and Wood	Discrete Cell Control	PPC	✓
	Mahmoodi, Dooley and Starr	An Investigation of Dynamic Group Scheduling Heuristics in a Job Shop Manufacturing Cell	PPC	X
Aug 90	Chu and Tsai	A Comparison of Three Array Based Clustering Techniques for Manufacturing Cell Formation	P-M Grouping Method Comparison	X
	Rajamani, Singh and Aneja	Integrated Design of Cellular Manufacturing Systems in the Presence of Alternative Process Plans	P-M Grouping New Method	X
	Askin and Chiu	A Graph Partitioning Procedure for Machine Assignment and Cell Formation in Group Technology	P-M Grouping New Method	✓
Jul 90	Gupta and Seifoddini	Production Data Based Similarity Coefficients for Machine-Component Grouping Decisions in the Design of a Cellular Manufacturing System	P-M Grouping New Method	X
May 90	Logendran	A Workload Based Model for Minimising Total Intercell and Intracell Moves in Cellular Manufacturing	P-M Grouping New Method	X
Apr 90	Shafer and Meredith	A Comparison of Selected Manufacturing Cell Formation Techniques	P-M Grouping Methods Comparison	✓
	Kuo and Inman	A Practical Heuristic for the Group Technology Economic Lot Scheduling Problem	PPC	✓
Mar 90	Rockwell and Wilhelm	Material Flow Management in Cellular Configurations for Small-lot Circuit Card Assembly	CM System Performance P-M Grouping and PPC	✓
Feb 90	Kumar and Chandrasekharan	Group Efficacy: A Quantitative Criterion for Goodness of the Block Diagonal Forms of Binary Matrices in Group Technology	P-M Grouping Solution Evaluation	X
	Sassani	A Simulation Study on Performance Improvement of Group Technology Cells	PPC	✓
	Al-Qattan	Designing flexible Manufacturing Cells Using a Branch and Bound Method	P-M Grouping New Method	X

Date	Authors	Title	Topic	
Jan 90	Silver	Deliberately Slowing Down Output in a Family Production Context	PPC	X
	Srinivasan, Narendran and Mahadevan	An Assignment Model for the Part Families Problem in Group Technology	P-M Grouping New Method	X
	Harhalakis, Nagi and Proth	An Efficient Heuristic in Manufacturing Cell Formation for Group Technology Applications	P-M Grouping New Method	✓
Vol 27 Dec 89	Flynn	Critical Machines Preventative Maintenance Policies for Group Technology Shops	Maintenance	X
	Silver	Shelf Life Considerations in a Family Production Context	PPC	X
	Wei and Kern	Commonality Analysis: A Linear Cell Clustering Algorithm for Group Technology	P-M Grouping New Method	X
Oct 89	Globerson and Millen	Determining Learning Curves in Group Technology Settings	Learning Curves	X
	Mosier	An Experiment Investigating the Application of Clustering Procedures and Similarity Coefficients to the GT Cell Formation Problem	P-M Grouping Method Comparison	X
Sep 89	Gunasingh and Lashkari	Machine Grouping Problems in Cellular Manufacturing Systems: An Integer Programming Approach	P-M Grouping New Method	X
	Wemmerlöv and Hyer	Cellular Manufacturing in the US Industry: A Survey of Users	Survey of Practice	✓
Aug 89	Hyer and Wemmerlöv	Group Technology in the US Industry: A Survey of Current Practices	Survey of Practice	✓
Jul 89	Seifoddini	A Note on the Similarity Coefficient Method and the Problem of Improper Machine Assignment in Group Technology Applications	P-M Grouping New Method	X
Jun 89	Chandrasekharan and Rajagopalan	GROUPABILITY: An Analysis of the Properties of binary data matrices for Group technology	P-M Grouping New Method	X
May 89	Shtub	Modelling Group Technology as a Generalized Assignment Problem	P-M Grouping New Method	X
Vol 26 Sep 88	Co and Araar	Configuring Cellular Manufacturing Systems	P-M Grouping New Method	X
Jul 88	Choobineh	A Framework for the Design of Cellular Manufacturing Systems	P-M Grouping New Method	X
May 88	Kusiak	EXGT-S: A Knowledge Base System for Group Technology	P-M Grouping New Method	✓
Mar 88	Booth	Beavers - Changing to Low Inventory Manufacturing	JIT/Cells Case Study	✓
	Burbidge	Operation Scheduling with GT and PBC	PPC	X
	Parnaby	A Systems Approach to the Implementation of JIT Methodologies in Lucas Industries	JIT/Cells Methodology	✓
	Rolstadås	Flexible Design of Production Planning Systems	PPC	X
	Zelenovic and Tesic	Period Batch Control and Group Technology	PPC	✓

Date	Authors	Title	Topic	
Vol 25 Dec 87	Kumar and Vanelli	Strategic Subcontracting for Efficient Disaggregated Manufacturing	P-M Grouping New Method	X
	Flynn	The Effects of Setup Times on Output Capacity in Cellular Manufacturing	PPC	X
Nov 87	Banerjee and Flynn	A Simulation Study of Some Maintenance Policies in a Group Technology Shop	Maintenance	X
Jun 87	Chandrasekharan and Rajagopalan	Zodiac - An Algorithm for Concurrent Formation of Part Families and Machine Cells	P-M Grouping New Method	X
May 87	Ballakur and Steudel	A Within-Cell Utilization Based Heuristic for Designing Cellular Manufacturing Systems	P-M Grouping New Method	✓
Apr 87	Kusiak	The Generalized Group Technology Concept	P-M Grouping New Method	X
Mar 87	Wemmerlöv and Hyer	Research Issues in Cellular Manufacturing	Topic review	X
Jan 87	Zelenovic, Ćosić, Šormaz and Šišarica	An Approach to the Design of More Effective Production Systems	P-M Grouping New Method	✓
	Askin and Subramanian	A Cost Based Heuristic for Group Technology Configuration	P-M Grouping New Method	X

Appendix C
Processes for Designing Cellular Manufacturing Systems

Hill's (1971) Process for Socio-technical Systems Design

i. *Initial scanning.* Identification of the main characteristics of the production system and its environment to determine the main problems. This stage covers layout, organisational structure, system inputs and outputs, the transformation process, the main types of variance and their source, the relationship between the production system and its containing department/business unit, and the main production and social objectives of the system.

ii. *Identification of unit operations*: the main phases in the production process that converts inputs into outputs.

iii. *Identification of key process variances and their interrelationship.* deviations from standard arising in the nature of the production process (not the technical equipment or the social system) that significantly affect the ability of the production system to pursue its objectives. Criteria suggested for identifying the significance of variances are their impact on quantity or quality of production, or on operating or social costs. A matrix is used to explore the relationships between variances.

iv. *Analysis of the social system.* Identification of the main characteristics of the existing social system. A key objective of this stage is to determine the extent to which key variances are at present controlled by the social system. This is achieved through compiling a table that details, where variances occur, where they are observed, where they are controlled, who controls them, what tasks are performed to control them, what information is obtained from where to enable control to take place. Also included in this stage are: analysis of auxiliary activities performed by workers, and their relationship with variance control activities; mapping of physical or geographical relationships between the various roles in the production system, and their relationship over time (shift patterns etc); recording of worker flexibility and knowledge of each others roles; identification of relationships between pay and the various roles in the production system; assessment of the roles against psychological needs, and identification of areas of frequent malfunctioning.

v. *Men's perception of their role.* Obtains an understanding from the workers of how well they feel their jobs satisfy their psychological needs.

This concludes the analysis of the production system itself and it is expected that several redesign proposals will have emerged. The analysis goes on to the consider the impact of some external systems upon the production system.

vi. *Maintenance system.* Maintenance variances and the extent to which they are controlled are determined. The extent to which maintenance tasks should be taken into account in the design of operating roles is assessed.

vii. *Supply and user systems.* Identification of variances that are passed into the production system by the systems that supplies raw material, or by the systems which dispatch or use the products of the production system. Possibilities for controlling these variances closer to the source are considered.

viii. *Environment and development plans.* Identification of those forces (such as development plans and general policies) operating within the wider environment that either effect the ability of the production system to achieve its objectives, or are likely to lead to a change in its objectives in the near future.

ix. *Proposals for change.* Gathering of all the proposals developed in previous stages for assessment of viability testing against the production and social objectives of the system. An action plan can then be formulated.

Pasmore's (1988) Change Model for Socio-technical Systems Analysis and Design

i. Define scope of the system to be redesigned.

ii. Determine environmental demands.

iii. Create vision statement.

iv. Educate and organise members.

v. Create change structure.

vi. Conduct socio-technical analyses.

vii. Formulate redesign proposals.

viii. Implement recommended changes.

ix. Evaluate changes / redesign.

Process Stages of the Lucas Methodology for Manufacturing Systems Redesign

i. *Business and market strategy:* The aim of this stage is to develop a set of guidelines to direct manufacturing systems design. First the levels of performance necessary to be competitive are defined along such dimensions as sales per employee, stock turn ratio, lead times selling price, product cost and measures of quality. Through the use of SWOT and situation analyses, products demands, life cycles and competitive positions should be identified. The output of this phase should be a detailed plan of volumes and variety over time, along with a clear statement of how manufacturing should support strategic objectives.

ii. *Manufacturing systems engineering strategy:* Having developed a clear set of objectives for the manufacturing system it is now possible to begin to design an appropriate manufacturing system. This stage begins with data collection to describe the current manufacturing system for example, bills of materials, product routings, machine capabilities, capacities, and reliabilities, supplier details. The designer is encouraged to look ahead through the process to determine data requirements. In practice, this is likely to result in some back-tracking to collect data that is found to be pertinent at a later stage. Pareto analysis is recommended to identify important parameters. Part-machine groupings and relationships between groups are determined, using Production Flow Analysis (Burbidge 1989) or Rank Order Clustering (King and Nakornchai 1982), to provide an architecture with a simple flow from raw material to finished product. This may result in a refinement of existing make-buy arrangements in order to deal with parts that don't neatly fit into the proposed new structure. Steady state design involves detailed allocation of machine capacity and human resources to cells based on average expected operating conditions. Job design and personnel policy are aligned with the new business objectives and the new organisation. The training necessary to achieve this is identified. Reduced levels of support required from service departments are also identified along with any requirements for supplier development. Dynamic behaviour of the system is then explored using simulation tools.

iii. *Business systems engineering strategy:* The production control system is then designed to take advantage of the simplified flow system and modular organisation. MRP is advocated to plan medium term material requirements, while day to day control is devolved as far as possible to the shop floor. The use of kanban is encouraged where it is applicable, while period batch control is the preferred option for the cells with high variety. Integration of the manufacturing information system with the other business information systems is then designed.

iv. *Integration with Financial Strategy:* An implementation plan is developed for the proposed system, and presented to management along with a financial analysis that details the costs, benefits, risks, and cash flows, associated with the project.

Process Stages of Wu's (1992) Methodology for Manufacturing Systems Design and Analysis

i. *Analysis of Situation:* Involves identifying the need for change, formation of a team and the allocation of tasks and responsibilities, and the compilation of a list of the symptoms indicating problems with the current manufacturing system. This stage then proceeds to describe the current manufacturing system using cross referenced databases of production technology, products, processes and personnel. Physical and control systems descriptions are also developed, for example using $IDEF_0$. Static and dynamic analyses are then undertaken to determine the root causes of the symptoms listed. Market and product analyses are beyond the scope of this methodology but their importance and influence on MSD is recognised.

ii. *Setting Objectives:* This stage creates a view of the desired future state of the manufacturing system. Variables and target values are identified, that balance the needs of individual projects and the long term goals specified by the corporate strategy. Comparing the desired future state with the current situation reveals the design task for the following stages.

iii. *Conceptual Modelling:* Identifies the building blocks (manufacturing and controlling functions) required of the system, including make-buy analysis. Defines the relationships between these functions and develops the basic principles by which the system will work. After evaluation, promising concepts are selected and taken forward for detailed design.

iv. *Detailed Design:* Transforms the conceptual model into detailed specifications that can be used for implementation. This involves selection, organisation and layout of production technology, determination of batch sizes and provision of storage facilities for buffer stocks, and the selection of materials handling devices. Control system design includes the process design, database design, selection and location of hardware and the allocation of managerial responsibilities.

v. *Evaluation and Decision:* Assesses the design solution against the initial objectives set out for the design, and determines whether the new system will generate a sufficient rate of return to justify the investment when compared with the option of leaving things unchanged. Major evaluation points come after conceptual modelling and after detailed design. A balance approach is advocated including the use of the Analytical Hierarchy Process where intuitive assessment is required in addition to quantitative analysis. Cash flows and risk assessment are also included in the project appraisal.

Process Stages of the Drama Methodology (Bennett and Forrester 1993)

i. *Market and Environment:* SWOT analysis of economic, sociogovernmental, customer, competitor and technical factors. Codetermination of corporate policy (profitability, growth, quality, customer service, personnel) and market strategy (geographical and product markets addressed, competitive edge criteria).

ii. *Manufacturing Strategy:* Manufacturing's contribution and response to the market strategy. Includes auditing current capabilities, decisions about make-buy and the degree of vertical integration, and the setting of manufacturing performance targets.

iii. *Organisation:* Design of the organisation structure (demarcation of responsibility and lines communication) and state (culture, employment climate, flexibility etc.).

iv. *Justification:* Selection of investment appraisal approach to generate a business case for a new or modified production system.

v. *Project Management:* Determination of a policy for the formation of a project team and the identification of appropriate project management tools and techniques.

vi. *Physical System Design:* Selection of the type of material flow path required, decisions regarding the type of automation of inter and intra module transportation and its integration with processing equipment, and also decisions regarding the degree of centralisation with regard to storage, tooling and work instructions. The type of storage is also defined.

vii. *Control and Integration:* Determines the balance of push and pull for production planning and control. Establishes stock holding policies, decides the degree of centralisation of the information system and selects the type of shop floor data collection

viii. *Work Design:* The choice of work organisation within the production system addresses such issues as worker flexibility, responsibility for quality and operator tasks, etc.

ix. *Implementation:* Plans the implementation with regard to timing and resourcing.

x. *Evaluation:* Establishes a framework and approach for evaluating the design and the design process.

Appendix D

Benefits of Quality Function Deployment

Raises the Voice of Customer. QFD focuses the design process on the customer, ensuring that technical trade-offs reflect the needs of the customer and that customer interface people understand the technical trade-offs (Hauser 1993).

Competitive Context QFD quantifies the competitive position and the opportunities available so that resources can be concentrated on satisfying those customer requirements that will provide the most competitive advantage.

Teamwork and Communication. QFD is a communication mechanism that uses the "Voice of the Customer" as a common language to facilitate multi functional team working by creating a common purpose, priorities and focus of attention (Sullivan 1986). A study by Griffin and Hauser (1992) showed that QFD increased integration and cooperation within a design team, and that communication among team members was enhanced even when the team crossed functional boundaries. Burn (1990) also notes that QFD provides a permanent and complete record of all the information currently available, providing a solid starting point for any future work to be undertaken or for any new team members.

Deals with Complex Interrelationships. QFD methodology provides a logical means of looking at interrelationships between the critical characteristics of the product that affect customer satisfaction. By their clear display in pictorial form a reasoned judgement can be made in design so that the confounding interactions are minimised (Burn 1990).

Systematic and Disciplined. "QFD offers a structured method to utilise the collective knowledge of management in defining the most critical characteristics of a product." (Maddux Amos and Wyskida 1991 p. 33). According to Eureka president of ASI, QFD allows for formalisation of knowledge, drawing out that information that engineers have in the back of their minds but don't bring out when talking at meeting (Vasilash 1989).

Proactive and Preventative. QFD aims to design positive customer requirements into the product rather than solely react to customer complaints (Akao 1990). It also moves and concentrates action and resources upstream in the design process to minimise the opportunity for problems to develop (Burn 1990).

There is very little published information describing the results and benefits of using QFD. Vasilash (1989) suggests however, that many companies are using QFD but are not publishing because the results are too important to their competitive advantage. This view is also expressed by Hjort et al (1992). Toyota Autobody's experience is the most widely quoted example: design costs cut by 61%, and lead times reduced by a third while simultaneously improving the quality of their product (Burn 1990; Hauser and Clausing 1988; Sullivan 1986). However, sufficient similar claims have been made by other companies to suggest that QFD may consistently deliver these benefits. For example:

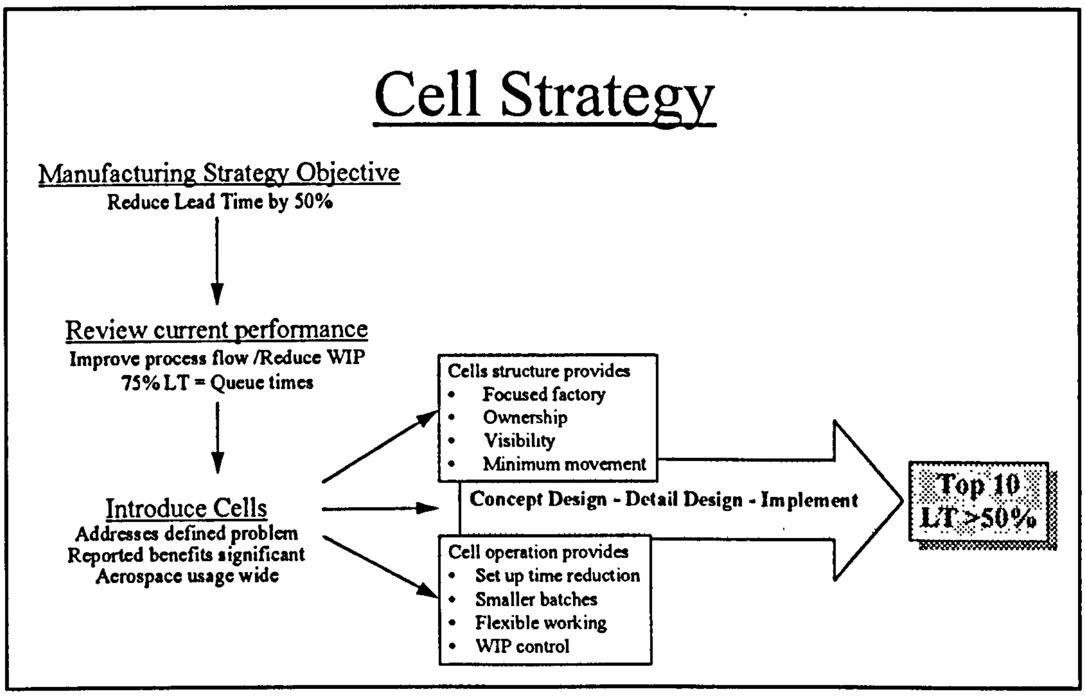
- Hauser (1993) reports that QFD enabled Puritain-Bennett to launch a new product in record time and at acceptable costs. More importantly, the product was so well received by the market that the company forecast a five-fold increase in sales.

- Comparing a product designed using QFD with a previous model, Nichols (1992) writes that Digital achieved a 75% reduction in concept phase time, a 40% reduction in engineering phases needed to get their product to market , and a 25% reduction in unnecessary product features.

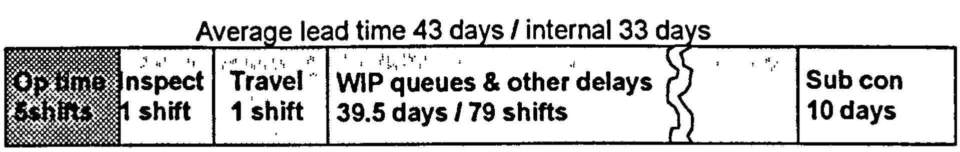
- Vasilash (1989) reports the experience of an Ernst and Whinney manager as being, that QFD generally results in a 30-50% reduction in design cycle times, 20-60% reduction in start-up costs, and a 20-50% cut in warranty claims.

Appendix E

Supplementary Information: Case Study



Lead Time Breakdown



- Part No xxxxxxxxx: (Batch = 51)
  - Internal throughput efficiency 6%
  - Stock turns = 5 = 1 day per op WIP queue
  - Irregularities: quality problems & schedule changes
- Knock-on Effects
  - WIP = £1M
  - Interest = £50,000K
  - Quality: 4% rejects ~ 20% of sales

Ideals of Lean Manufacture

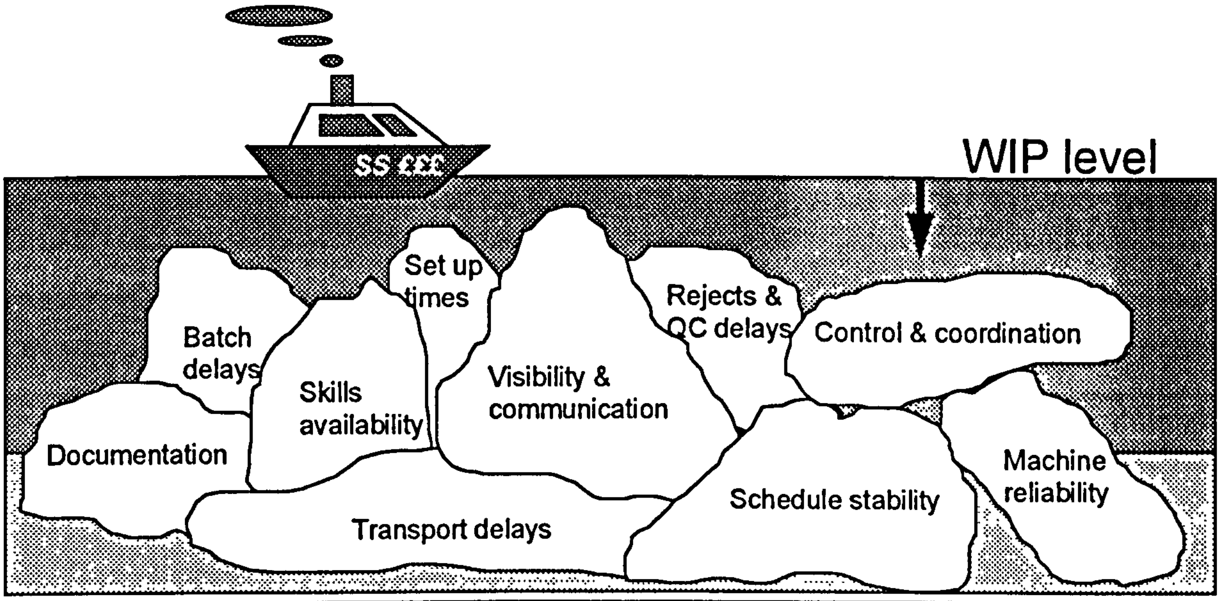
- Operations
- Transport
  - Zero transport
- Inspection
  - Zero defects passed to next process
- Delays
  - Zero work-in-progress
    - »Delivery of material only when required for production
    - »Production only when required by next process
    - »Batch size of one
  - Zero set up times
  - Zero break downs
  - Zero defects

So why is WIP important ? ....

Causes of Work in Progress

- Unbalanced and unsynchronised flow between processes
- Safety buffers to avoid machine breakdowns or quality rejects from delaying succeeding processes
  - eg Kitting bond
- Security

WIP Hides Problems



We must find & remove rocks to allow WIP reduction

How Cells Help

- Ownership of product and production objectives
- Reduce distances between processes
  - Improve visibility of status / progress / problems
  - Improve communication between processes
  - Reduce transport times
- Control of process & resources
  - To meet production objectives & solve problems
- Simplify routing complexity, reduce sources of variation
- Good foundation for further improvement
  - Work place organisation, set up reduction, reduce documentation generated, local PPC, source inspection etc
  - Support TQM & continuous improvement

Focus For Improvements

- Layout & facilities improvement
  - First cut, refinement is inevitable and desirable
  - Increase local wash facilities
- Work place organisation
  - Visual control
  - Good housekeeping
- Work flow balancing
  - Reduce set up times
  - Reduce transfer batch quantities
  - Control build up of WIP between processes
- Set up reduction
  - Improve preparation
  - Hold most used programmes in the machine
  - Improved work place organisation
- Local scheduling & control
  - Notice boards for production plans, progress & performance measures
  - Progress to key operations
  - WIP locations / levels
- Simplify documentation system
- Quality / inspection
  - Cell quality performance measured
  - Shift focus from operation to product
  - Cell focused quality engineers

Performance

Mission

- To reduce lead times by 50% in support of the business objectives
  - To provide quality products which meet the customer requirements
  - To meet all delivery schedules in the quantities required
  - To manufacture at a low cost by achieving high levels of productivity

Physical Environment

- **Objectives**
- Visibility
  - work progress, machine condition, tools, documents etc
- Minimum waste movement
  - work & people
- Minimise delays due to unexpected m/c down time
- Improved communication
- Safety
- Good work environment
- Impressive appearance

How

- Cell layout
- Organised
  - Place for everything, no clutter in work area
- Clean & tidy
  - Everything in its place
- Preventative maintenance
- Off-shop eating areas & personal lockers
- Good lights
- Painted floors

Quality

- **Objectives**
- Minimum inspection delays
- No defects passed on to next process
- Continuous improvement

How
- Approved operators & self inspection
- Need for overcheck eliminated
- Quality issues resolved quickly in cell
  - local quarantine
  - cell focused assessor, engineer
  - operator involvement
- Local measure & display of quality performance
- Improved process control exploiting SPC

Work Flow Control

- **Objectives**
- Minimise delays between processes
- Control level of WIP
- Accurate knowledge of work status
- Even load across resources of a cell

How
- Clear production targets
- Ownership of necessary resources to complete products
- In cell scheduling & control
  - Clear & visual mechanisms: eg. WIP locations & max levels, planning boards
- Quick set ups
- Small batches
  - (no grouping of batches)
- Local measure & display of lead time & delivery performance
- Stable plan
- Smoothed schedule

People

- **Objectives**
- Minimise delays through lack of available skills
- Minimised wasted labour
- Continuous improvement
- Robust organisation
-

How

- Multi-skilling & flexible team working
  - Basic machine maintenance
  - In cell inter operation material handling
- Multi-machine manning
  - Inc. across m/c types
- Operator involvement in problem solving
- Minimise short term movement between cells
- Medium to long term cell rotation to maintain skill base

Future Development

- **Objectives**
- Assure future of company
- Continuous improvement
-

How

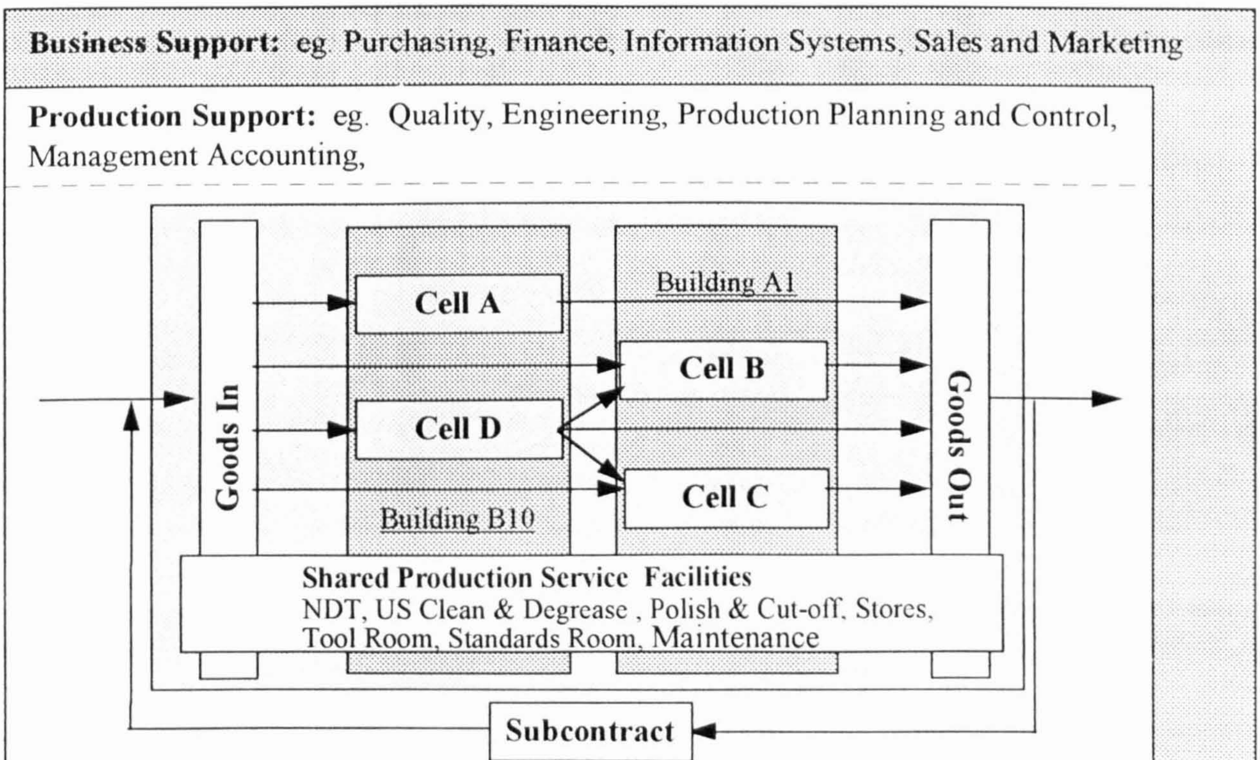
- New products engineered to fit cells
- Cells developed to meet changing requirements
- Investment to support lean working
  - eg more small m/cs rather than few big m/cs: local wash, vibro polish
- Supply chain development to meet cell needs
- Development of internal systems to suit cells & lean working

Support Services

- **<u>Objectives</u>**
- Support services to compliment cell operation

<u>How</u>

- Service contracts specifying cell & service centre responsibilities
  - eg. delivery times & quantities, & turnaround times



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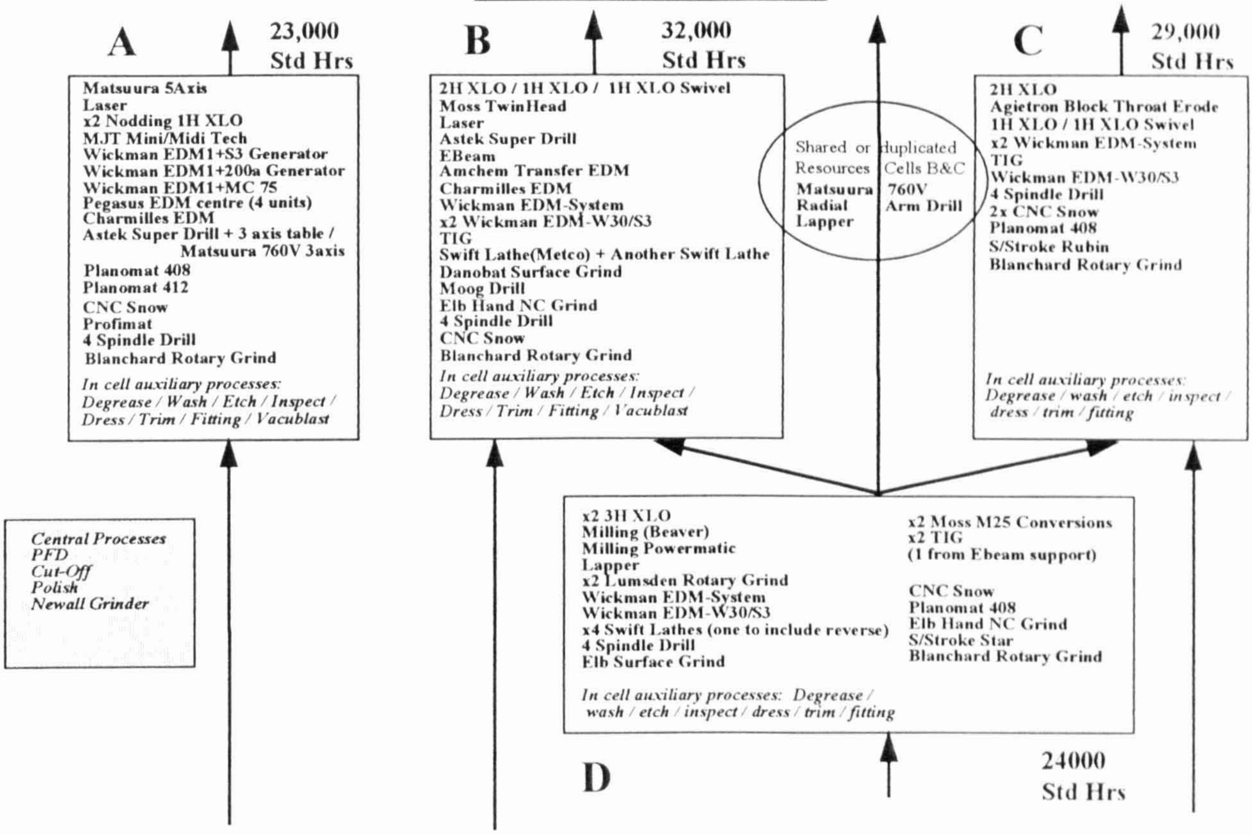
PFA Module Summary With Machine Loads

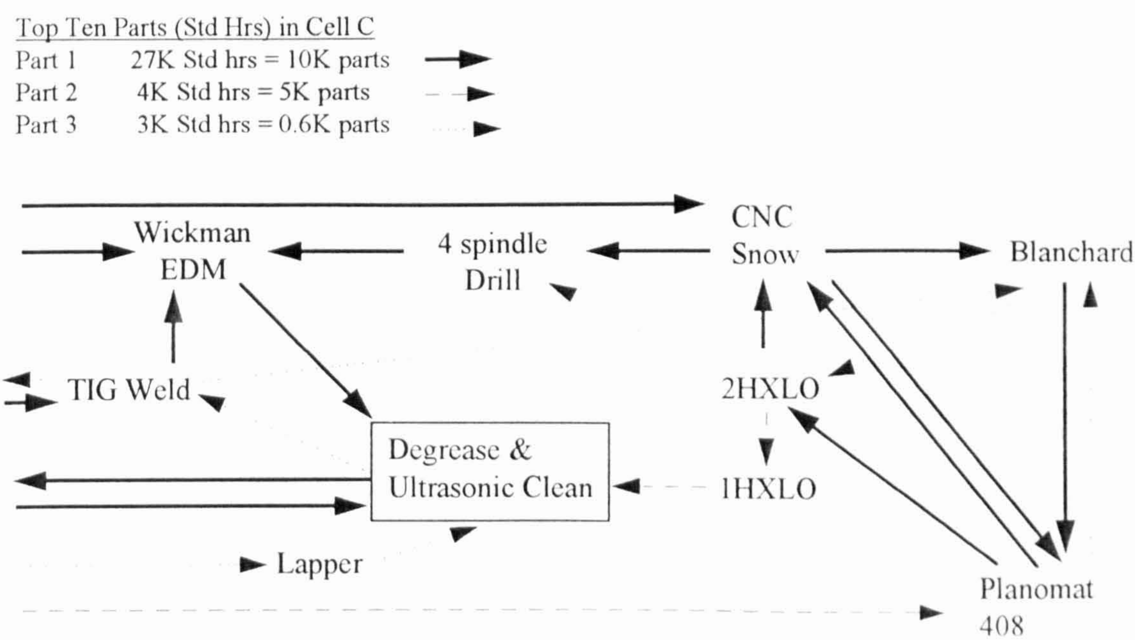
Module	W/C	W/CENT DESCRIPTION	M/Cs	SICGE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	24	25	26	27	28	29	30
1	573	MOSS TWINHEAD FANTAIL ERODE	1	1S	28%																												
2	571	AMCHEM TRANSFER EDM	1	1S		83%																											
3	551	MATSUURA VF600CNC MILL 5 AXIS	1	1S			101%																										
4	46	NEWALL GRINDER	1	1S		0%		0%																									
5	563	NODDING SINGLE HEAD XLO	1	1S			48%		176%																								
6	501	ELECTRON BEAM WELD	1	1S						28%																							
7	550	MILLING POWERMATIC	1	2I							0%																						
8	577	ASTEK SUPER DRILL	1	2I								8%																					
9	561	S/HEAD XLO - SWIVEL	5	2I	5%					30%			17%																				
10	549	MATSUURA 760V 3 AXIS	1	2I			20%		36%					0%																			
11	575	AGIETRON BLOCK THROAT ERODE	3	2I											31%																		
12	574	CHARMILLES EDM	2	2I	14%		2%			39%						21%																	
13	521	BLOHM PLANOMAT 412	1	2I			25%						1%	0%			4%																
14	578	MOSS M25 CONVERSIONS	2	2I														79%															
15	565	LAPPER - E4 AREA	1	2I						1%									6%														
16	564	LAPPER LATHE AREA	1	2I										0%						1%													
17	552	CINCI.VERT/HORZ MILL	N/A	2I	0%					3%										0%	0%												
18	562	TWIN HEAD XLO	2	2I		87%		45%		29%									38%			70%											
19	546	3 HEAD XLO GRIND NO1	1	2I						0%						42%				1%	0%		4%										
20	560	XLO GRIND	2	2I	2%					56%		10%			72%							0%		31%									
21	579	LASER DRILL	2	2I	9%	17%	41%	81%	14%	11%		2%												2%	55%								
22	530	LUMSDEN ROTARY GRIND	2	2I							0%			0%						4%			9%			79%							
23	568	WICKMAN EDM - SYSTEM	7	2I	15%	30%	258%	0%	7%	60%			3%						32%	1%		102%	0%			37%							
24	70	TIG WELD	4	2I	11%					58%	0%	0%			0%			71%	37%	1%		34%	0%			0%	16%						
25	570	WICKMAN EDM - W30/S3	5	2I	3%	40%		24%		88%		2%			73%				20%	1%				11%		30%	4%	4%					
26	538	SWIFT LATHE	6	2I	1%	41%		20%		0%	0%			3%						9%	0%		9%			236%		5%	13%				
27	525	ELB HAND NC GRIND	2	3C		17%	2%	10%		28%		1%			3%									4%			22%			0%			
28	527	CNC SNOW GRIND	4	3C	3%		48%						1%		17%							247%				29%	0%	4%	34%		17%		
29	518	ELB SURFACE GRIND	1	3C						0%		1%			6%	26%				2%			6%			0%						0%	
30	520	BLOHM PLANOMAT 408	3	3C	14%	1%	119%	0%	46%	32%		2%	1%	0%	9%				14%	0%		149%		4%		78%	42%	1%	2%	1%	0%		13%

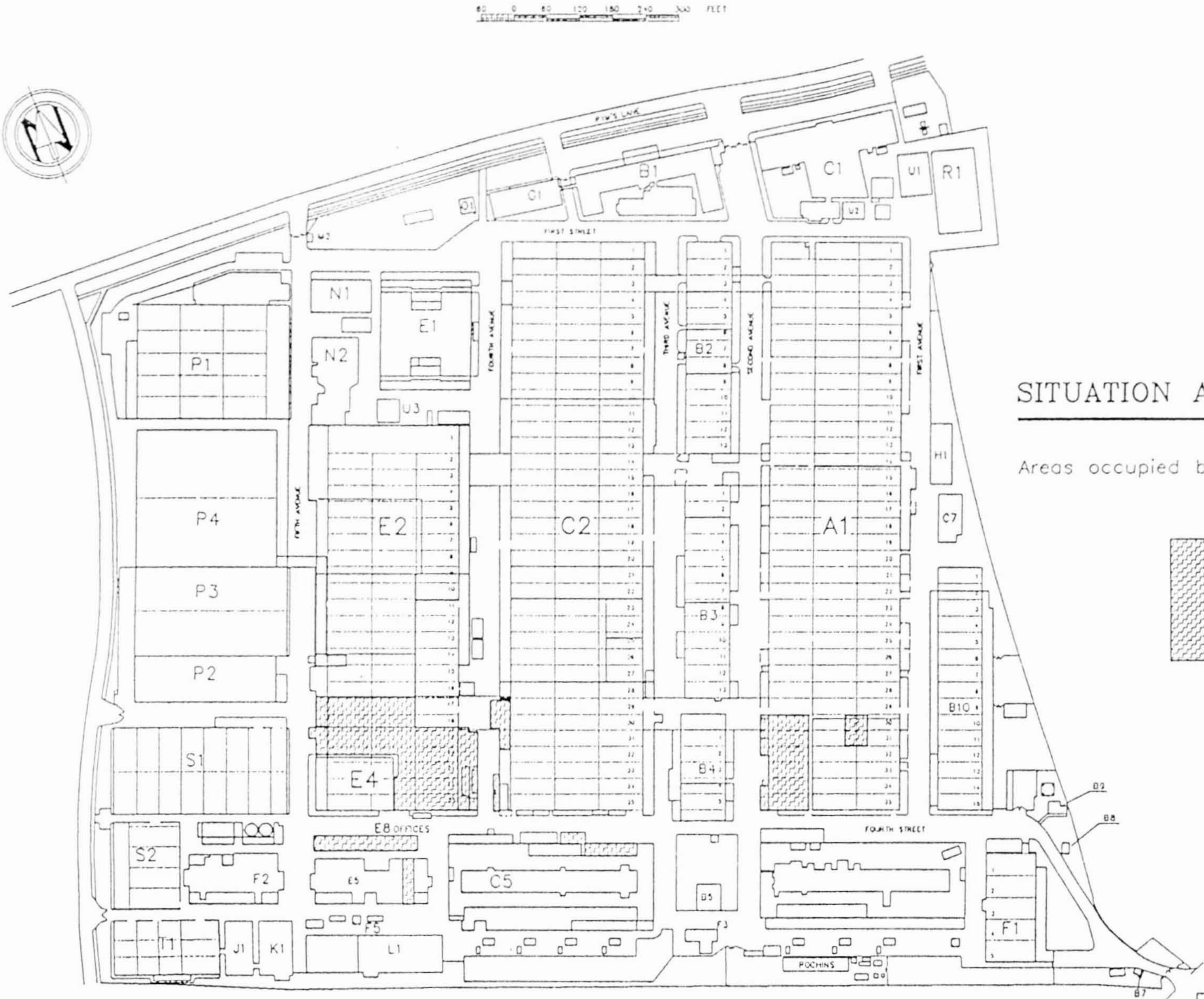
Cells: Machine Groups

(Based on 1997 Loads)



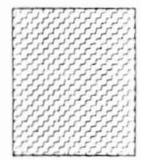
Cell C - Dominant Flows



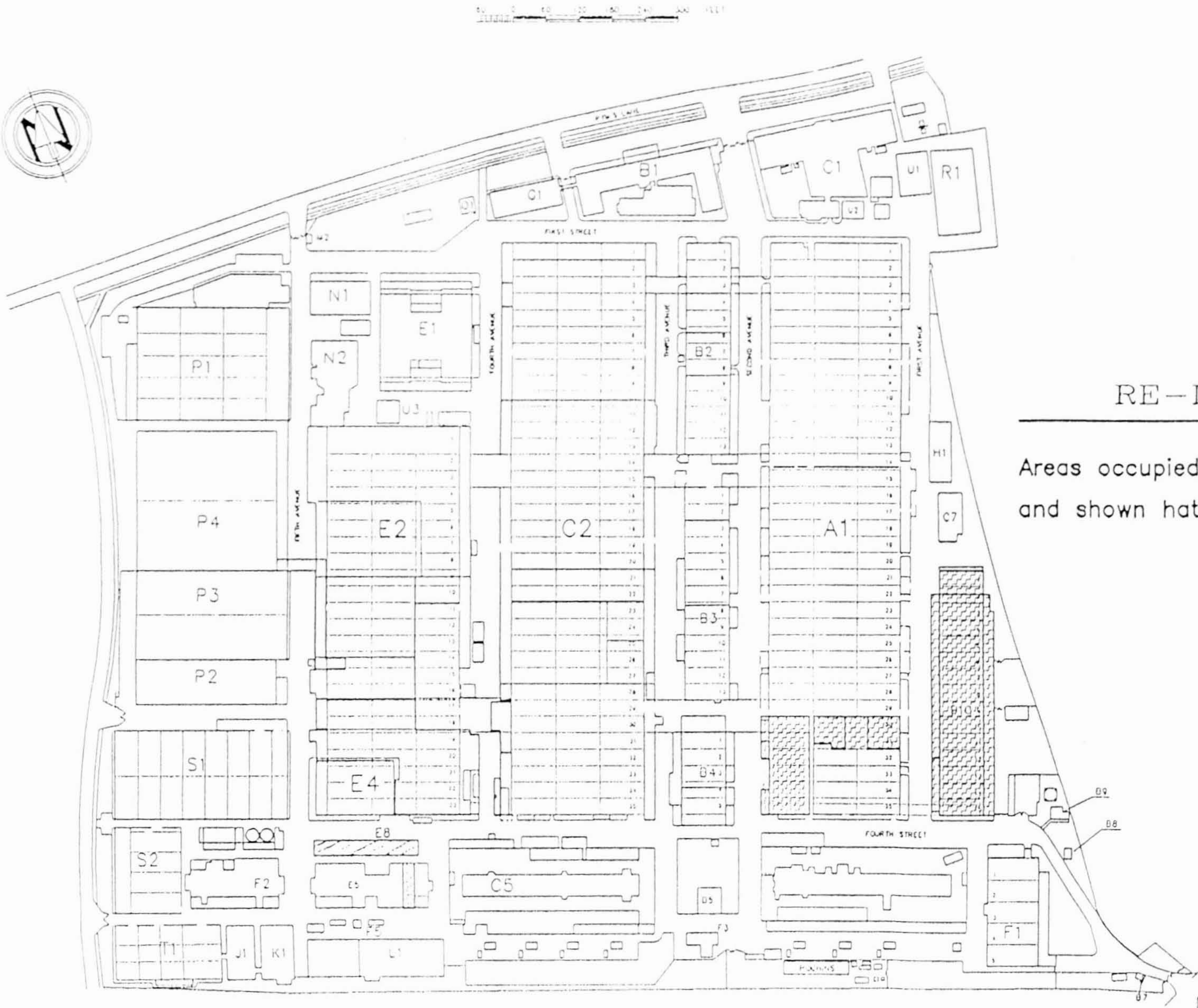


SITUATION AS NOW:-

Areas occupied by shown hatched :-



PROJECT ENGINEERING DEPARTMENT	
SITE DRAWING	
DRG No. MOVE1	SCALE:
DATE Jan. 1995	REVISION No.

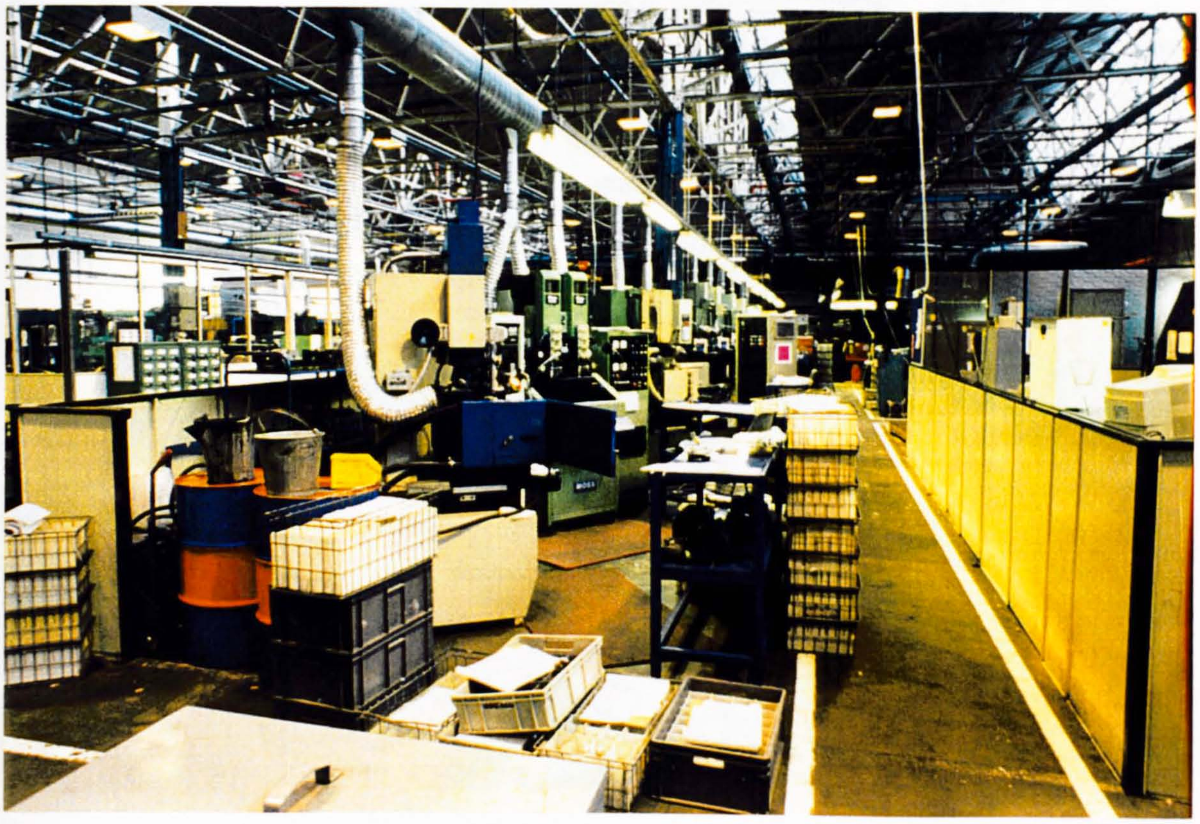


RE–LOCATED:–

Areas occupied by now rationalised and shown hatched :–

PROJECT ENGINEERING DEPARTMENT	
SITE DRAWING	
DRG No. MOVE1	SCALE:
DATE Jan. 1995	REVISION No.

Functional Organisation of EDM Machines



Functional Oraganisation of CNC Grinding Machines

Preparation of New Factory

Point of Use Storage in Cellular Layout

Appendix F

Prompt Sheets for Semi Structured Interviews

1. Survey of Consultants Cell Design Methodologies

a. Describe your process for designing cellular manufacturing systems.

    Do you have any published material on the method or cases?

    Is this a company developed process or personal process?

    What is the extent to which this methodology has been tested?

        How many times, who for, and does it include implementation?

b. Description of the execution of each stage.

    What is to be achieved at each stage?

    How is this determined?

    How is it achieved?

    How is success evaluated?

    How long is it expected to take?

    How are the tasks related? - what are the contingencies?

c. What issues arise at each stage and how they are dealt with?

d. What are usually the most significant problems to be overcome to ensure a successful outcome?

e. How important is the organisation of products and equipment to the systems performance. Compare with control system design, job design, quality system design?

2. Review of the New Design Process

Introduction

Describe purpose of interview

Present summary of cell design process under review

Tailoring Cellular Manufacturing Concept

How important do you think it is that the cellular manufacturing concept is tailored to suit the operating environment of each specific manufacturing system?

How well do you think we have achieved this?

How important is it that the design is guided by strategic performance improvement objectives?

How well do you think we have achieved this?

Do you think it is necessary to proceed in a series loops, moving between design and implementation?

Determining Important Effects of Cellular Manufacturing

How useful is it to identify important effects as a intermediate step in the identification of important cellular manufacturing features?

Did the general model help to identify cellular manufacturing effects that otherwise may not have been identified.

How useful is the general model of cellular manufacturing?

Are there any drawbacks of using such a model?

Could the model be improved & how?

Determining Important Features of Cellular Manufacturing

Does the matrix help to identify the relative importance of cellular manufacturing features?

Did the general model of cellular manufacturing help to identify any features that otherwise may not have been identified?

What are the benefits of using the matrix?

What are the difficulties of using the matrix?

Could these difficulties be overcome, or is their a better way of achieving the same benefits?

Do the benefits outweigh the difficulties?

Determining Support Features

Having identified the key features that are required to achieve the desired benefits, how important do you think it is to identify further "enabling" cellular manufacturing features?

How well do you think we have done this?

Presentation of the Concept Design

Does a network diagram adequately describe the interaction of cellular manufacturing features?

Could the presentation of the concept design be improved?

General

Are their any issues that you feel are important that are not covered by the questions I have asked?

Would you consider using this process for designing cellular manufacturing systems?