THE UNIVERSITY *of* LIVERPOOL

The Application of Quality Function Deployment Principles in Manufacturing System Design

Thesis submitted in accordance with the requirements of The University of Liverpool for the degree of Doctor in Philosophy

by

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ABSTRACT

The manufacturing system design function is primarily responsible for the provision of resources for the operations function. The optimum configuration of the technological resources within a manufacturing system will enhance manufacturing capabilities and facilitate the achievement of business objectives. It is increasingly recognised that a strong and important relationships exist between manufacturing strategy and the technological decisions in manufacturing system design. However, there appears to be limitations with regard to *how* these two entities are integrated within a systems design.

This research is concerned with the methodologies and tools for manufacturing system design. Firstly it examines the general trends of industrial practices in manufacturing system design with respect to the scope of applications of current methodologies and tools, as well as how manufacturing companies address the dimensions of manufacturing strategy in manufacturing system design decisions. This is achieved through an extensive literature search followed by a questionnaire survey on a sample of British manufacturing companies.

The second part of the research involves the development of a methodology to enhance the link between the strategic requirements of the market and manufacturing system design decisions. The objective of this new methodology is to adapt the principles of Quality Function Deployment (QFD) approach in the definition and specification of a class of advanced manufacturing system based on the strategic requirements. The tools within the QFD approach are utilised in order to facilitate the translation of strategic business objectives at the top level to the tactical and operational decisions of the manufacturing system design. This can be achieved through two main stages : (1) The requirements to be deployed are decomposed into various details and they are assigned to different levels within a manufacturing hierarchy, and (2) Based on the different combinations of the priorities obtained, the requirements are deployed using the four planning matrices defined. The final matrix provides the relative importance of the various parameters of the system elements which can be used in decisions related to equipment selection phase of manufacturing system design. Tests are performed on some simulated examples to provide initial verification of the methodology.

The proposed methodology can be considered as a generative approach to decision making model in which a 'best' set of decisions is derived based on objectives as input. It demonstrates the integration of the elements of manufacturing strategy in the manufacturing system design decisions. This new approach has the distinct advantage of providing transparency of decisions to resolve complex system design situation. The deployment of the requirements using the planning matrices has resulted in the design decisions taken to be more focused and highly tractable.

For my wife Norizah,
and
children: Abdullah, Sakinah, Abdul Rahman, Muhammad Syafiek,
Ahmad Zubair and Adam Fathi.

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In The Name of Allah, The Most Gracious, The Most Merciful

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INTRODUCTION

1.1 Background

The main objective of any company is to make money in an efficient manner so as to be profitable. This process of making money is generally achieved through a manufacturing system whose function is to produce products that meet specific market requirements. The system utilises limited resources, such as machines, labour, material and energy in an integrated way so as to turn raw material into saleable products. Currently it is widely recognised that manufacturing companies are operating in a different new competitive environment which is characterised by the following trends [51] : (a) world-wide dissemination of expanding scientific knowledge; (b) the striking growth in the number of global competitors; (c) fragmented markets and shifting customer preferences; (d) diverse and transforming process technologies - leading to greater flexibility and responsiveness; and (e) a proliferation in the number of technologies relevant to any given product. These trends in the competitive environment have produced changes in the manner in which orders are won. Although they are still relevant, the traditional way of winning customer orders based on cost and product quality, are no longer sufficient. Increasingly, companies are competing on the non-cost basis of flexibility and dependability.

Faced with these changes, manufacturing firms must develop the right manufacturing strategy and they need to utilise appropriate planning and design methodology of manufacturing systems. A review of the literature has shown that the existence of an important link between manufacturing strategy and manufacturing technology decisions is recognised [113,143,191,209,295]. The design of manufacturing systems must be such that the rising expectations and diverse requirements of customers are accommodated, while still maintaining the economic level of operational competence. The most effective design process should have the mechanism to integrate the strategic objectives and the market requirements with the technical and engineering requirements.

1.2 Manufacturing Strategy-Technology Relationship

The potential technical capabilities of technological processes and methods must be matched with opportunities to meet the corporate objectives. These objectives could include: fast response to market demands, better product quality, reduced cost, enhanced performance, better asset utilisation, shorter development lead-times, minimum work-in-progress, and flexibility. In operational terms manufacturing system must be designed such that it contributes to the competitive position of the company by meeting the following targets [144,187]: product always meets market demands, a product design which meets specifications and facilitates lowest cost and maximum quality production and maintainability, minimum engineering and production cycle time, zero defects, zero time between manufacturing operations, zero set-up time, fewest number of manufacturing operations, zero raw material and finished goods inventory, and minimal management and support organisational structure.

The fit between a firm's manufacturing technology and its competitive strategy has traditionally been seen as the need for trade-offs between the competitive priorities. This arose because a particular manufacturing system (technology) cannot satisfy all priorities. The development of advanced manufacturing technologies such as Computer Aided Design (CAD), Computer Aided Manufacture (CAM), robotics, Flexible Manufacturing System, and Computer Integrated Manufacturing (CIM) has, however, changed previous notions about trade-offs between the priorities [63,93,109,179]. The new technologies are more flexible and highly integrated, making the production of numerous product variations almost as efficient as manufacturing large volumes of standardised products. Since the adoption of these technologies involve a huge investment and a high degree of uncertainty, manufacturing firms should give greater attention to the strategic level decisions.

1.3 Manufacturing system design

During the lifetime of a manufacturing system, an organisation goes through many phases of decision making related to the system: planning for the system, initial design, detailed design, installation, production planing, scheduling, operation, and on-going modifications or improvements. The central issues addressed in this research are concerned with the first two phases, i.e., planning for the system and initial design. During these phases the user determines the equipment requirements and transform these requirements into specifications.

Manufacturing system design can be conceptualised as the mapping from the performance requirements of manufacturing system, onto suitable values of decision variables. The performance requirements are expressed by values of certain performance measures such as time, quality, cost, and flexibility. The values of decision variables describe the physical design or the manner of operation of the manufacturing system [150, 283]. The types and the number of machines in a manufacturing system are examples of the decision variables.

Generally, the overall approach to manufacturing system design problem is to decompose it into sub-problems of manageable complexity, which are then treated separately. These problems are simplified and abstracted with the aid of assumptions. Methodologies and techniques are then developed to find optimal solutions to the simplified problems, and these often include involved mathematical analysis and computer programming [152,153,154,240]. Although these approaches provide a good opportunity for academic researches, yet industrial practitioners will find it prohibitive. In industrial practice, trial and error remains the most frequently used design approach [49]. Another shortcoming of the optimisation approaches is that, they normally fail to consider the strategic long-term issues facing the manufacturing organisation as a whole.

The importance of manufacturing system design and development in achieving the strategic business objectives is the basis of the present work. The design and development of manufacturing systems must support the firm's business needs and link with the objectives of the business plan. The strategic objectives must be able to be 'translated' into appropriate manufacturing system design parameters which subsequently form the platform for system specifications. Although many researches have been reported on the design of manufacturing systems, there is, however, limited publications on the manner in which manufacturing strategy is translated into the actual selection of the manufacturing capabilities.

1.4 Quality Function Deployment

Quality Function Deployment (QFD) was developed in Japan as an advanced quality system made up of an integrated set of quality tools and techniques to provide customer-driven products and services. In order to improve customer satisfaction by developing products/services that deliver more value, QFD improves the process of listening to the "voice of the customer" throughout the product development process. The focus of QFD is not only on what is required to satisfy the customer, but also on understanding how important things are to the customer. QFD has tools and techniques for the exploration and specification of customer requirements or "demanded quality." Once captured, the qualitative customer requirements are translated and deployed into quantitative technical requirements or "quality characteristics" in the "House of Quality" matrix. This is done at various levels of sophistication, ranging from four matrices [108] to thirty [138]. The customer requirements are broken down and analysed right down to the separate measures of production in order to ensure that the product satisfies these needs. Simply stated, QFD's fundamental objectives are to identify the customer, identify what the customer wants and identify how to fulfil the customer's wants.

Although QFD has originally been developed for product design and manufacturing process enhancement, it can be employed to address virtually any business situation requiring a decision making involving a multitude of criteria, requirements or demands. It has been demonstrated to have significantly broader applications such as strategic planning decisions, R & D project planning, vendor and software selection, Total Quality Management action decisions and technical concept selection [281], software development [135], market expansion analysis [182], the design of engineering curricula [147], and health care services [77]. There is, however, no published work on the application of QFD in manufacturing system design.

1.5 Research Aim and Objectives

Sections 1.2, 1.3 and 1.4 have briefly described the three interrelated topics that will serve as the foundations for the research work reported in this thesis. Having recognised the importance of linking the manufacturing system design decisions with corporate plans and goals, a research need is identified for some intermediate mechanism for translating the strategic requirements into a form directly applicable to support manufacturing system design decisions.

Hence, the *aim* of the research work reported in this thesis is to investigate the feasibility of extending the application of the principles of Quality Function Deployment (QFD) in the design of manufacturing system. The emphasis of the project is on the manifestation of the manufacturing strategy in the specifications and selection of the manufacturing equipment.

The research aim is to be accomplished via the following objectives:

1) To assess the general trends of industrial practices in manufacturing system design with respect to the nature of relationships that exist (or not) between manufacturing strategy and manufacturing system design decisions; and the features and extent of application of manufacturing system design methodologies and tools.

2) To develop a theoretical framework in defining the requirements of manufacturing systems design, based on the strategic requirements of cost, quality, delivery and flexibility.

3) To establish a procedure of deploying the strategic requirements down to the specifications and parameter identification of the manufacturing equipment.

4) To undertake initial testing on the methodology developed, in order to demonstrate its potentials and limitations.

1.6 The Research Approach

The research reported in this thesis has been pursued in the following manner:

- An extensive literature survey was carried out to investigate the following aspects: current thinking on the relationship between manufacturing strategy and manufacturing system design; the theoretical foundations of manufacturing systems; the major parameters that influence manufacturing systems design; and the design approaches and tools used for manufacturing system design. This was supplemented by visits to companies involved in advanced manufacturing.

- Familiarity with Quality Function Deployment technique was achieved through the author attending a 3 Day Practitioner Course in October 1993. This was supplemented by in-depth literature review of the published work in the Proceedings of the QFD Symposium (USA) and other references.

- An industrial survey was carried out on a sample of UK manufacturing companies involved in discrete part manufacturing. The objective is to build an understanding of the current practices of manufacturing systems design, including the methodologies, approaches and tools being used. Another aspect of the survey is to evaluate the relative success (or otherwise) in achieving the potential benefits of advanced manufacturing systems, with respect to the stated strategic objectives. The strategic objectives being treated as synonymous to the set of competitive priorities in the manufacturing strategy model.

- Based on the principles of the QFD approach, a methodology was developed, as a planning and requirements deployment tool in order to translate the most fundamental business objectives (or competitive priorities) into technical parameters in the actual specifications and selection of the manufacturing capabilities. The competitive priorities represent the most important customer requirements in a competitive environment. This translation or deployment is achieved through a series of matrices that relate the requirements (WHATs) and the manner in which they are fulfilled (HOWs). A top-down hierarchical approach will be utilised in deploying the competitive priorities into the actual specification of the system. The hierarchical framework of the requirements is to consist of five distinct levels: *strategic requirements; production system requirements; manufacturing system performance requirements; manufacturing system task requirements; and manufacturing system elements characteristics.*

- The development of the methodology made use of the QFD/Capture Software package as a means of handling and manipulating the data and information.

- A few hypothetical examples were used to provide some initial verification on some features of the methodology. The examples focus on the equipment selection in the system planning and initial design of Flexible Manufacturing Cell for producing metal parts.

1.7 Outline of the Thesis

An introduction to the thesis by way of describing the significance and the changes that are facing manufacturing industry is given in this chapter. An overview of the three facets to the research work, namely, the relationship between manufacturing strategy and manufacturing system design decisions, conceptual understanding of manufacturing system design, and Quality Function Deployment is also included. The aim and objectives of the research, as well as the outline of the approach are also presented.

Chapter 2 consists of three major sections. The first section provides an overview of the various definitions and objectives of manufacturing systems. The types and classifications of manufacturing systems will be elaborated. Particular emphasis is given to the advanced manufacturing systems. The second section gives detail discussion on the subject of manufacturing system design. The problems that need to be tackled and the decisions that need to be made during the design process are elaborated. Factors that enhance or limit the design process are deliberated. The various aspects of current design methodologies and tools are also addressed. The last section of the chapter provides the various models of manufacturing strategy and how they relate to manufacturing system design decisions. The strategic or competitive advantages of cost, quality, delivery and flexibility which form the basic requirements of manufacturing system design will also be discussed.

Chapter 3 provides detail description of Quality Function Deployment. The mechanics of the approach and the different approaches of its implementation that have been developed will be elaborated. The different areas in which QFD has been used will also be discussed, which will illustrate the flexibility of the approach.

Chapter 4 reports on the planning and results of the industrial survey that has been carried out to investigate the nature of manufacturing system design in a section of the UK manufacturing industries. The discussion will include findings from the questionnaire as well as the conclusions that can be drawn from the study.

Chapter 5 outlines the theoretical framework of the proposed methodology developed. The chapter describes the concept of macro planning, the hierarchical model of manufacturing systems and the hierarchical framework of manufacturing requirements. For each of the competitive advantages, the derivation into five levels of requirements, namely strategic, production system, manufacturing system performance, manufacturing system task, and manufacturing resource will be presented.

Chapter 6 details the stages and problem solving steps that are involved in the deployment of the requirements. The requirements at the higher level of the hierarchy are called the WHATs and the parameters in the lower level of the hierarchy are called the HOWs. The Analytic Hierarchy Process (AHP) which is a tool for multi criteria decision making problems is incorporated in the evaluation of the degree of importance of the strategic level WHATs. Further deployment process takes into account the nature of relationships between the two levels of requirements. The relationships and the deployment of the requirements are graphically represented through a series of planning matrices.

Chapter 7 focuses on examples to investigate the viability and limitations of the methodology in the initial design of flexible manufacturing cell. The findings with regard to the outcome of the system requirements deployment, the effect of the variation in the degree of priority of the strategic objectives on system parameters, and the effect of changing scale used are discussed.

Chapter 8 contains the conclusions, research contributions and recommendations for further work.

CHAPTER 2

MANUFACTURING SYSTEMS DESIGN

2.1 Introduction

The purpose of this chapter is to review the characteristics and important role of manufacturing and manufacturing systems for a business organisation. The conceptual definitions of manufacturing system and manufacturing system design will be introduced. Section 2.2 discusses the significance of systems view in the analysis of manufacturing systems. It will also elaborate on the characteristics and types of advanced manufacturing systems with particular emphasis on flexible manufacturing systems. Section 2.3 elaborates on the parameters influencing the manufacturing system design decisions. The various approaches and techniques of manufacturing system design will be presented in Section 2.4. Finally, Section 2.5 deals with the issue of the relationship between manufacturing strategy and manufacturing system design decisions.

2.2 Manufacturing Systems

2.2.1 Manufacturing and Production

Fundamentally, manufacturing is an organised set of activities devoted to the transformation of raw materials into marketable goods. The transformation or conversion processes are technological in nature and are called production processes [114]. CIRP [50], through its Technical Scientific Committee 'O' (optimisation) provided a unified nomenclature and definitions as follows: *Production* is defined in general as the output or result of industrial work in different fields of activity, e.g., agricultural production, oil production, energy production, and manufacturing production; *Manufacturing production* as an activity is the act or process (or the connected series of acts or processes) of actually physically making a product from its material constituents, as distinct from designing the product, planning and controlling its production and assuring its quality; *Manufacturing* is a series of interrelated activities and operations involving the design, materials selection, planning, production, quality assurance, management and marketing of the products of the manufacturing industries. As the distinction between the two terms is too fine, the terms 'manufacturing, and 'production' have often been used interchangeably in the literature on manufacturing [39].

2.2.2 Systems Concepts in the Context of Manufacturing

The description of systems concepts in the literature [30, 44, 114, 223, 273] shows that the complex nature of manufacturing can be studied via systems approach. Mitchell [184], for example, has used the open system paradigm in viewing manufacturing enterprises and their settings, as well as in explaining effective solution strategies to the design of advanced manufacturing system.

Based on the systems concept of manufacturing, a *manufacturing system* is defined as a combination of manufacturing processes which takes inputs and produces outputs with higher or added value [26, 114, 204]. It includes the actual equipment composing the processes and the arrangement of those processes. The entire manufacturing system must be controlled in order to regulate levels of inventory, movement of material through the plant, production rates, and product quality. The manufacturing system is considered to be within a wider environment of the production system, which refers to the total company or enterprise. Figures 2.1 - 2.2 serve to illustrate the definition.

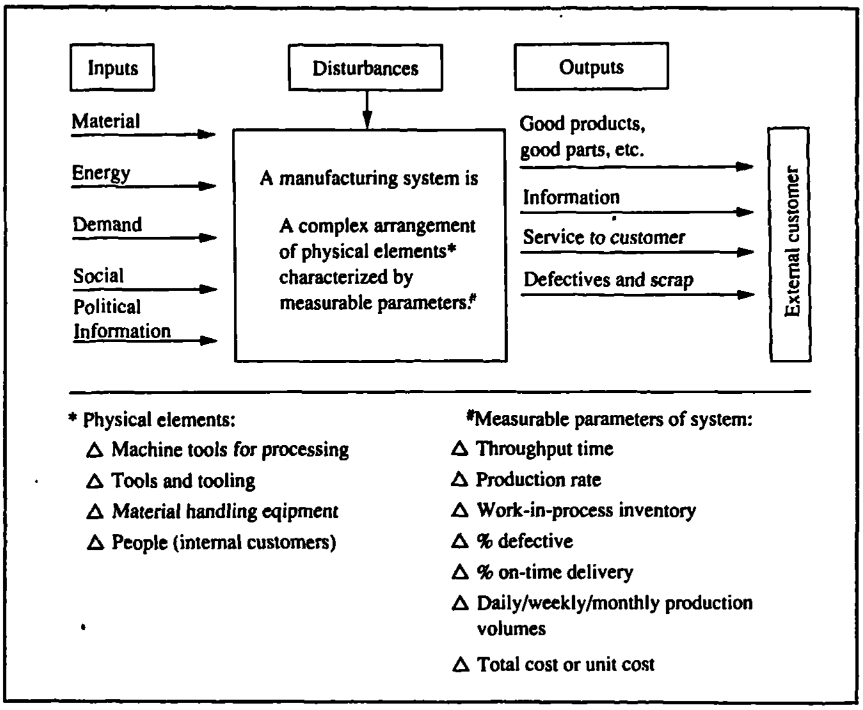


Figure 2.1 Definition of manufacturing system [26]

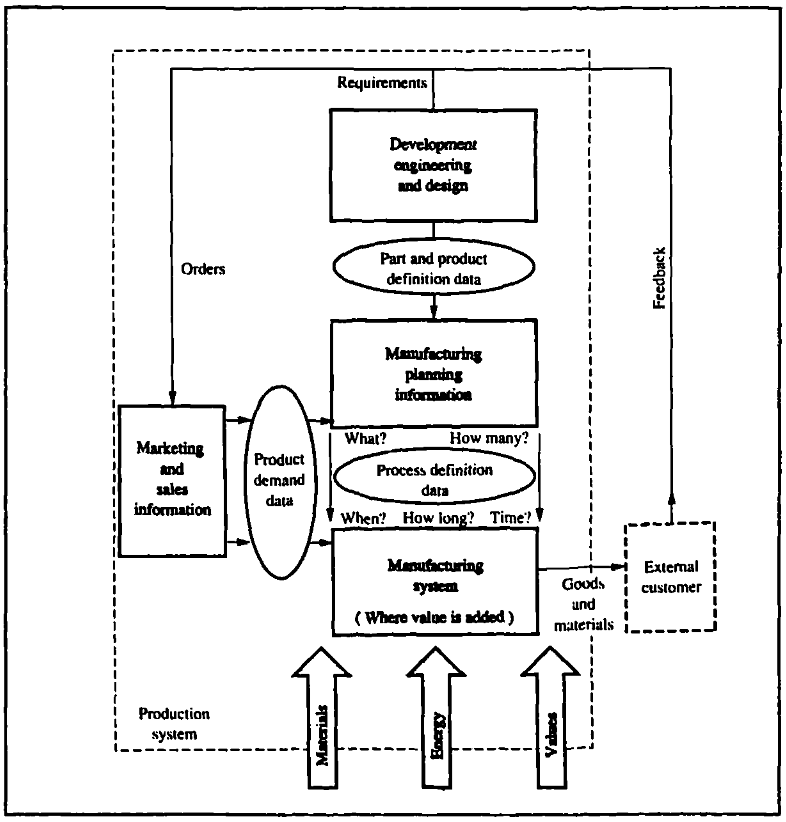


Figure 2.2 Manufacturing system within the production system environment [26]

The important physical elements of all manufacturing systems are people, processes, material-holding and handling equipment. Viewed in systems perspective, the raw materials are inputs to the system, the manufacturing process as transformation and the products as outputs of the system. The measurable parameters for a manufacturing system are the performance measures of the system, and are very different from those of the individual machines or elements that make up the system. These could be considered as the emergent properties of systems. Another important aspect of systems concept to be considered in the context of the present work is the dynamic behaviour of the relationship that exists between the manufacturing system with the wider system environment of competitive market.

2.2.3 Objectives of Manufacturing Systems

In order to be successful, manufacturing companies must strive for simultaneous economic product manufacture and market competitiveness. The ability to be responsive to the market demand efficiently, such system features should be present: short lead time, low operating costs, low inventory investment, high quality, advanced product and process technology, high resource utilisation, and improved customer service and reliable deliveries.

These features therefore exemplify the type of objectives which must be translated into a manufacturing system design and specification. Furthermore they clearly illustrate the potential conflict between various design requirements which a final system specification must resolve. For example, high resource utilisation generally goes against improvements in flexibility demand and inventory management. Therefore, during its design and operation, manufacturing systems have to handle compromises and make trade-offs between conflicting requirements.

For any given set of objectives, however, there is no ideal manufacturing facility. The vastly varying production facilities is a result of the necessity to make trade-offs between conflicting objectives and the wide range of possible alternative element configurations. Thus no two systems are exactly alike. For each company, even those in the same markets, have their own unique requirements or anomalies in such things as the mode of working or method of production employed. Further differences are created by the way in which a company interacts with its social and business environment.

2.2.4 Classification of Advanced Manufacturing Systems

The actual configuration of a manufacturing system in terms of the layout and the type and number of elements that it constitutes depends on a number of factors such as the type of products and the nature of demand. High demand for a product justifies a dedicated process whilst low volume demand points to a flexible process able to meet the manufacturing requirements for a number of different products. Another dimension that is important in the configuration of manufacturing system is the knowledge of the available technologies. The combination of different technologies may result in different manufacturing systems. The range of system complexity for advanced manufacturing system is illustrated in Appendix A [189]. In addition to the technological factor, the level of investment also dictates the actual constituents of the system.

Modern manufacturing systems for discrete part manufacturing are designed along five main principles: transfer line, dedicated (batch) flow line, flexible manufacturing system, flexible manufacturing cell and numerical control machine [26, 98, 218]. This classification is based on the layout of the manufacturing system. The layout in turn is influenced by two major parameters: the production rate or quantity, and the number of different types of product to be manufactured. The scope of each type of manufacturing system is illustrated in Figure 2.3.

Transfer Line

Transfer lines are very efficient when producing parts in large volumes at high output rates. The workstations are usually custom made, fixed type automation machines, which once they have been set up, are seldom reconfigured. The limitation of this type of system is that the parts must be identical. A changeover in part design requires the line to be shut down and retooled.

Special System

The special system occupies the region between the transfer line and the flexible manufacturing system. Also called batch flow line principle [218], it is designed to produce a very limited number of different parts, perhaps 2 to 8 [98], in the same manufacturing family. The object is to minimise set up and tool change times.

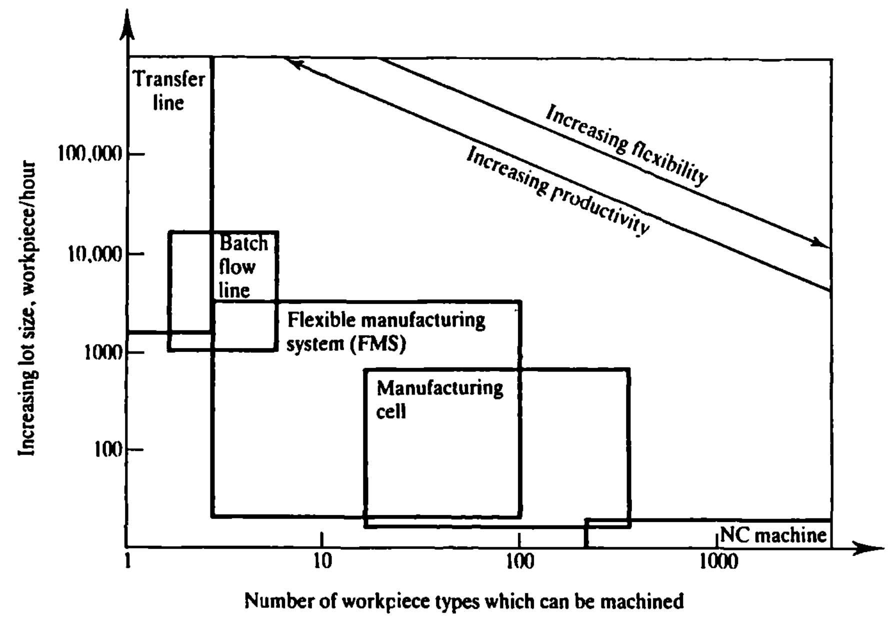


Figure 2.3 Modern Manufacturing Concepts [218]

Flexible Manufacturing System

The term flexible manufacturing system, or FMS, refers to a set of computer numerical controlled (CNC) machine tools and supporting workstations that are connected by an automated material handling system and are controlled by a central computer. The system has the flexibility of the job shop and its efficiency approaches that of the flowline. The system is used to manufacture several part families (4 to 100) at production rates per part of between 40 and 2000 per year. Parts are loaded and unloaded at a central location in the FMS. Pallets are used to transfer parts between machines. Once a part is loaded onto the handling system it is automatically routed to the particular workstations required in its processing.

Flexible Manufacturing Cell

A flexible manufacturing cell consists of between 1-6 CNC machine tools with automatic tool changing and automatic loading/unloading of parts from associated buffer. It is the most flexible but generally has the lowest production rate, among the flexible systems. The number of different parts manufactured in the cell might be between 40 and 800 and annual production levels for these part could be between 15 and 500.

Numerical Control Machines

The numerical control (NC) machine performs the typical job shop operations. When a workpiece is to be machined, the raw material and the tools are set up and the NC program is entered. The program selects and directs the tool to machine the desired surface contour. The flexibility of this machine tool is very high; when a new part is to be machined, tools can be changed and a new part program is entered into the controller.

2.2.5 Other Methods of Classification

Traditionally, manufacturing systems have been classified into five principal types based on their layout and the nature of products. These are: project, jobbing, batch, line and continuous systems [26, 98, 113]. Other basis of classification methods have also been cited in the literature. These include the number of stages of production [114, 186], the nature of manufacturing and supply activities [287], the operating structure [96, 127], level of technology [42] and the product design and manufacturing complexities [17].

2.2.6 Flexible Manufacturing Systems

Flexible manufacturing system (FMS) represents the latest level of automation in the evolutionary process of improving the productivity and flexibility of the manufacturing equipment and systems. An FMS is a collection of production equipment logically organised under a host computer and physically connected by a central transport system [195, 198, 277]. FMS have been given a variety of different names, including 'variable mission manufacturing systems', and 'group technology manufacturing cells' or 'cellular manufacturing'.

The object of the FMS is to simultaneously manufacture a mix of part types whilst being flexible enough to sequentially manufacture different part type mixes without costly, time consuming, changeover requirements between mixes. Hence the approach is sometimes called as 'flexible manufacturing' [103], as the term is not just regarded as an expression of technology, but also as an expression of the capability to respond to market changes with a minimum of investment in stock or warehousing.

FMS or cellular manufacturing systems possess the following two fundamental characteristics: (1) parts to be machined are classified into different families, and (2) machines are arranged into cells according to the manufacturing requirements of a particular family. FMS has the capability of implementing the Computer Integrated Manufacturing (CIM) concepts on the shop-floor, and as a consequence achieving a batch size, which can be as low as one, and a highly effective and productive manufacturing method with the dynamically changing product life cycle of different products. As such, FMS can be regarded as a 'microcosm of the future computer-automated, optimised and integrated factory' [178].

The main incentives for introducing flexible manufacturing are reduced cost in production and adaptability to an ever changing environment. Among the benefits of installing the flexible manufacturing are [141]: benefits related to cost reduction programme (55%), benefits related to market response improvement (30%), and benefits related to flexibility in production (15%). A comparison of FMS with conventional manufacturing technology under various states of risk show that FMS's provide substantial productivity improvement, as shown in Table 2.1 [226].

Parameter	Performance	
	Conventional system	FMS
% of machine time the machine spends without parts	50	20
% of machine time that there is a part on the machine	50	80
% of time that the part is not being worked on while on the machine	70	21
% of time that the part is being worked on while on the machine	30	79
% of manufacturing lead time that the part spends either moving or waiting	95	90
% of manufacturing lead time that the part spends on the machine	5	10

Table 2.1 Comparison of conventional system with FMS [226]

2.2.6.1 FMS Subsystems

An FMS can consist of primary components such as machine tools, a material-handling system, and a supervisory computer control network. The secondary components include pallets and fixtures, load/unload stations, tool commissioning/setting, buffer stations, etc. Figure 2.4 shows a conceptual layout of an FMS [198]. All, or a subset of the modules shown are required for an FMS user to be able to implement the system. To integrate the equipment into a working system, functions are required from the FMS host computer and the data base system control. Detail account of the equipment and functions required for an FMS is given in references such as [198, 218, 245].

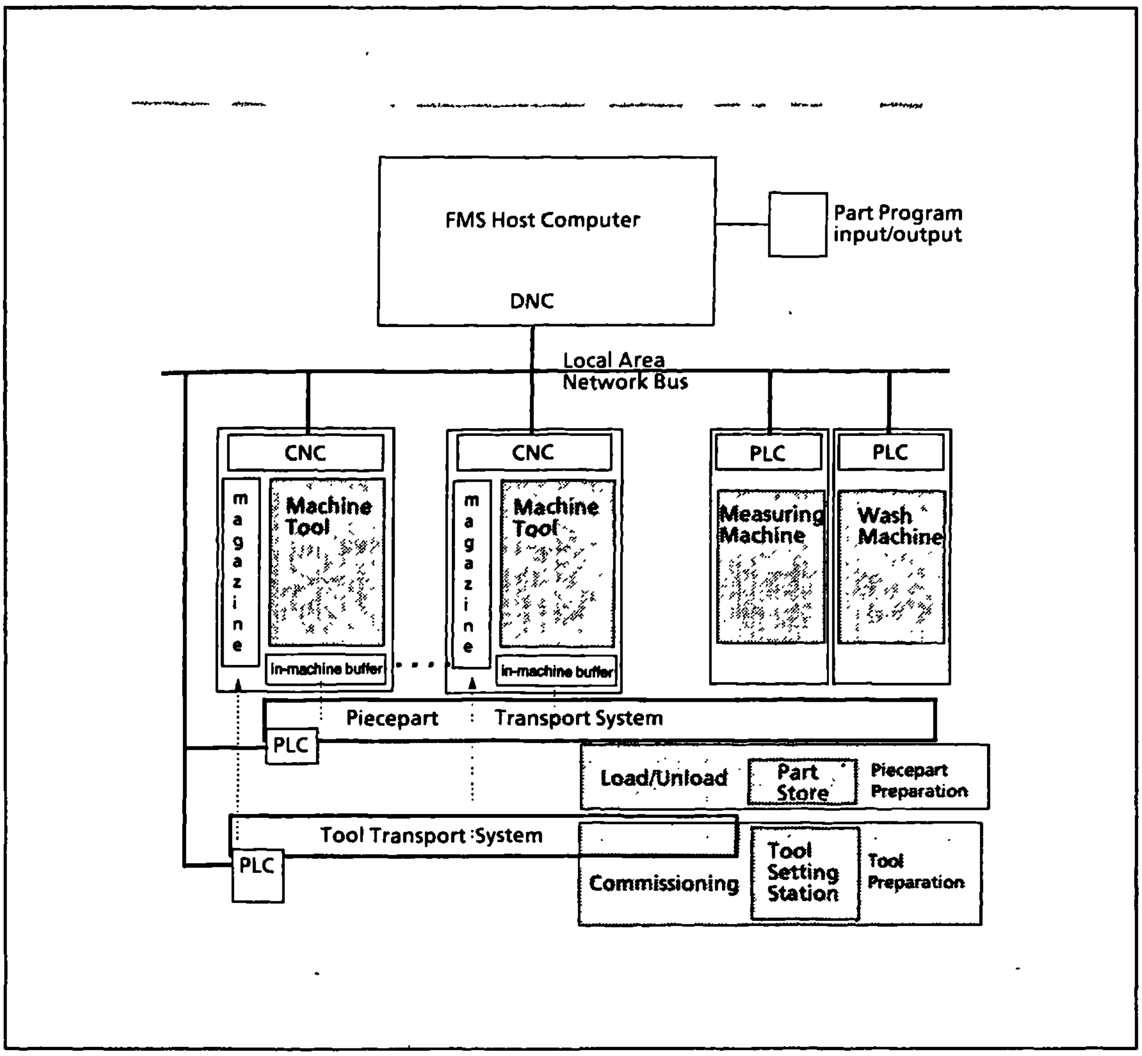


Figure 2.4 Conceptual layout of an FMS [198]

Processing system

A group of computer numerically controlled (CNC) machines forms the primary equipment that adds value to the workpiece being manufactured. The workpiece being either prismatic or rotational. Horizontal machining centres (HMC) and head indexers are typically used for machining prismatic parts. Prismatic parts rest in a fixture that is specially designed for the part during processing and loading/unloading. Rotational parts are those with a symmetrical quality to their cross section and are held in place by the lathe's chuck during machining. Robots are used for grasping the rotational parts for loading and unloading.

Material handling system

An automated and flexible material handling system permits jobs (on pallets) to move between any pair of machines so that any job routing can be followed. Conveyors, tow carts, rail carts, and automatic guided vehicles (AGV's) have been used. Tow carts are simple platforms on wheels that can be engaged by drive chains in the floor and carried along to the desired destination. Rail carts, which can be self-powered, are used when the workstations are in straight line. They can move bidirectionally. An AGV is a self-powered vehicle, which either follows a wire-guided path in the floor or self-guided.

Supporting equipment

A shuttle or a robot can be used as a mechanism for connecting the part movement system to the machine. Parts and their fixtures must be off-loaded from the transport system when they arrive at the destination. A flexible system could also include an automated storage and retrieval system for fixtures, tools, pallets, raw materials and workpieces. A co-ordinate measuring machine (CMM) can be incorporated for automatic inspection, where dimensions and location of features can be accurately measured.

System controller

As the brain of the FMS, the system controller keeps track of system status. System status involves the location of all parts, tools, and carts, including those waiting to be loaded, and operational status of each machine. Based on current status and production plans, the controller downloads commands to the individual system components. For machine computers with limited storage capacity to maintain part plans, the controller may store part programs, which may be downloaded to individual machines as required.

2.2.6.2 Types of FMS

Using the basic definition of FMS and the conceptual layout of an FMS in Figure 2.4 as a basis, many types of FMS configuration can be identified. Browne et al. [36] initially classify FMS into four types : flexible machining cell, flexible machining system, flexible transfer line, and flexible transfer multi-line. The classification scheme was later extended by using the type of material handling as the basis [255].

FMS's can also be differentiated by the manner in which the host computer handles the different requirements [198]. These result in five types of FMS:

- Sequential FMS, which manufactures one part batch type while planning and preparation is carried out for the next part batch type to be manufactured.
- Random FMS, which manufactures any random mix of part types at any one time.
- Dedicated FMS, continually manufactures for extended period, the same but limited mix of part batch types.
- Engineered FMS, which manufactures the same mix of part types throughout its lifetime.
- Modular FMS, which has sophisticated host and enables the system to expand their FMS capabilities in s stepwise fashion in any of the previous four types.

A structural taxonomy of FMS's based on the number of technological components and their arrangements (or annual production of parts and the number of different parts per system per year) is provided by Kusiak [150]. Five types of FMS configurations that result from this classification are graphically shown in Figure 2.5, namely, flexible manufacturing module, flexible manufacturing cell, flexible manufacturing system, flexible production system and flexible manufacturing line. These classes of FMSs can be characterised by four types of flexibility: FMM flexibility, material handling flexibility, computer system flexibility, and organisational flexibility.

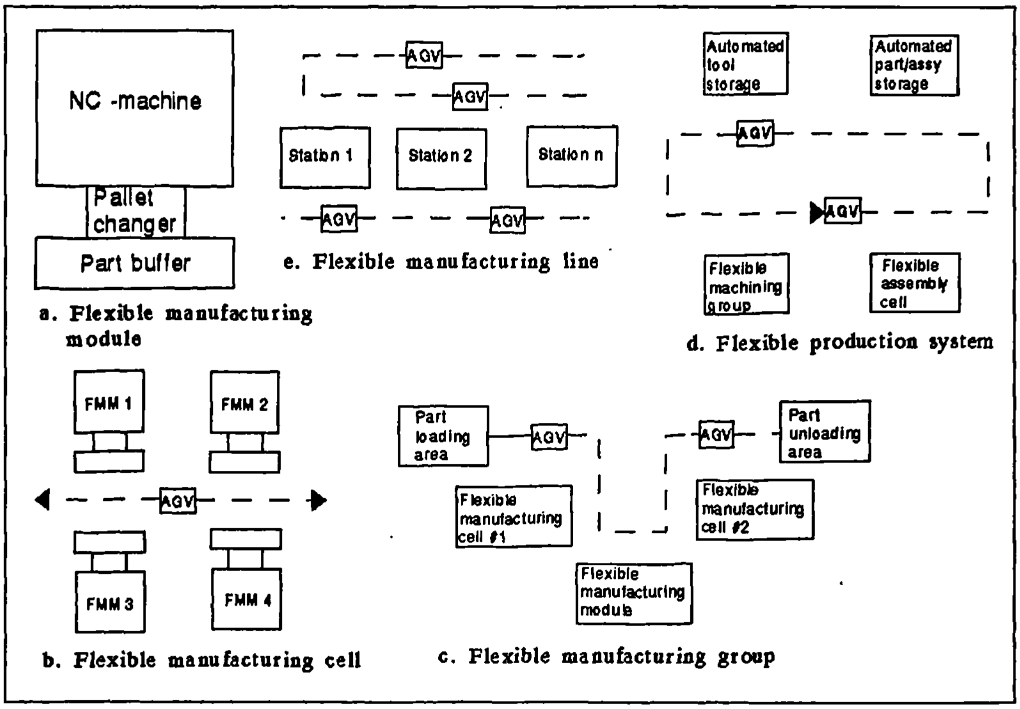


Figure 2.5 Structural taxonomy of FMS [150]

Based on the operational and control characteristics of the manufacturing systems, Maccarthy and Liu [168] classify FMS's into four configuration of increasing complexity):

1. A single flexible machine (SFM) is a computer controlled production unit which consists of a single CNC or NC machine with tool changing capability, a material handling device and a part storage buffer.
2. A flexible manufacturing cell (FMC) is a type of FMS consisting of a group of SFM's sharing one common material handling device.
3. A multi-machine flexible manufacturing system (MMFMS) is a type of FMS which consists of a number of SFMs connected by and automated material handling system which includes two or more material handling devices or is otherwise capable of visiting and serving two or more machines at a time.
4. A multi-cell flexible manufacturing system (MCFMS) is a type of FMS which consists of a number of FMCs, and possibly a number of SFMs if necessary, all connected by an automatic material handling system.

All the four types of FMS satisfy the fundamental definition of FMS. In this classification the attributes of material handling system are important in distinguishing different FMS configurations. The relationships and boundaries between the different FMS configurations are shown schematically in Figure 2.6.

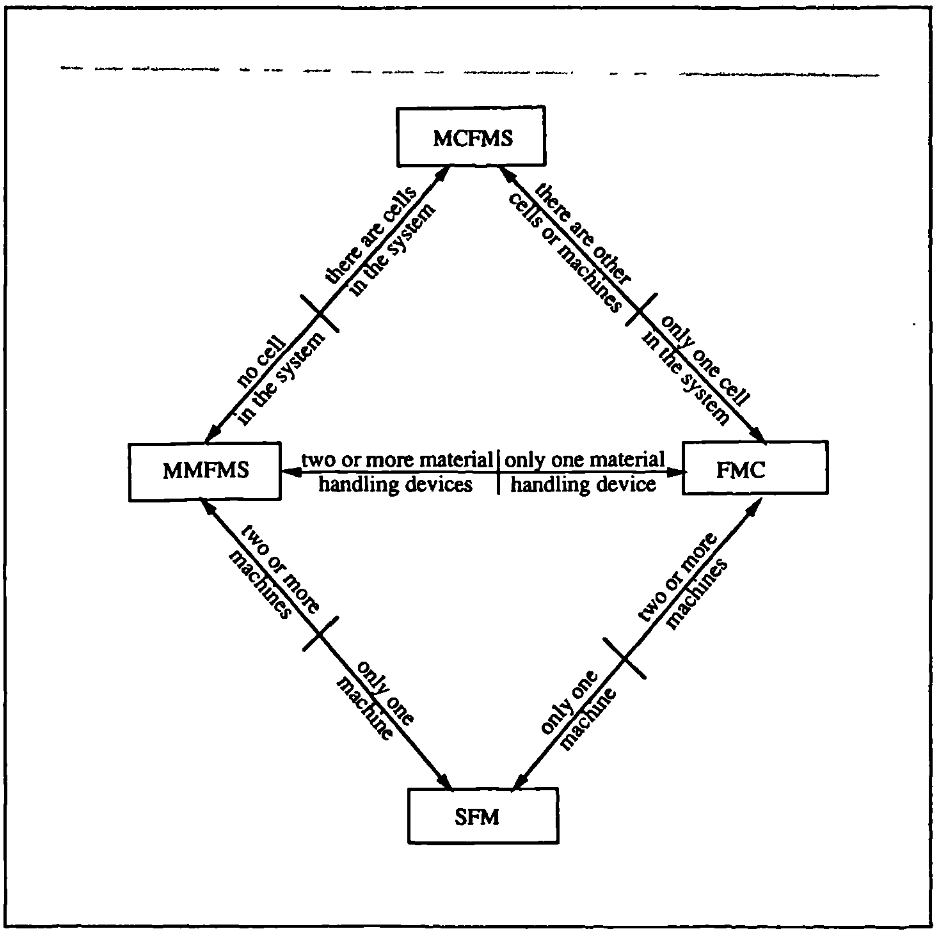


Figure 2.6 Relationships between different types of FMS. [168]

The description of the different types of flexible manufacturing systems shows the wide range of possibilities available to manufacturing organisations. There is no panacea solution to all the manufacturing problems. However, each manufacturing situation can be accommodated by one or more of the configurations. The choice of the most appropriate system configuration provides the opportunity for manufacturing automation even for companies with limited financial resources. Appropriateness in this case is dictated by the technical necessity and feasibility, i.e., whether implementing flexible manufacturing can meet the market requirements of the products.

Besides providing a medium for describing the flexible manufacturing systems with the essential characteristics and behaviour, the classification allows comparative evaluation and assessment. Furthermore, in research studies it provides a clear hierarchical framework for the study of operational and control aspects.

2.2.7 Flexible Manufacturing Cells

The discussion in the previous section has indicated that the two basic classifications of flexible manufacturing configurations are the FMS and the FMC. The two types of configuration are essentially the same except the size and the level of automation [97, 141]. Klahorst [141] for example, provides a guideline for considering the choice between an FMS and FMC, see Table 2.2. The dichotomy between a cell and a system can also be viewed in terms of the complexity of the configuration which results from functional integration [252] as shown in Figure 2.7. The fundamental similarity between a flexible manufacturing system and a flexible manufacturing cell is the fact that both are based on the principle of Group Technology or Cellular Layout.

• When part size and mass exceed 'jib crane' standard. • When production volume is in excess of two parts per hour. • When processing requires more that two machine types to complete a workpiece. • When more than five machines are required. • When phased implementation is planned so that material handling provisions can be incorporated.

Table 2.2 Guideline for using FMS [142].

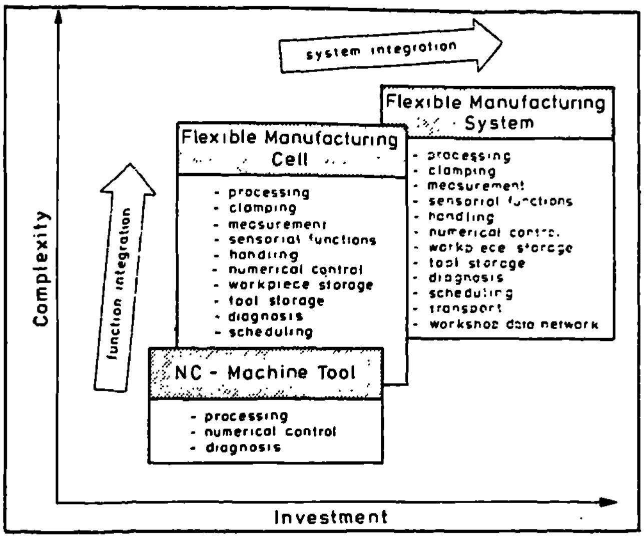


Figure 2.7 Differences between a cell and a system [252]

A manufacturing cell is normally regarded as the building block of the larger manufacturing system. There are many ways of viewing the cell of factory automation such as 'the smallest autonomous unit capable of sustained production' [290], 'having a small collection of machines which are closely co-operating with each other' [5, 25, 290], and 'as a 'bridge' from conventional manufacturing to Computer Integrated Manufacturing (CIM) and the Factory of the Future, [296].

Although having the potential for being extremely valuable, flexible automated manufacturing system have the associated technical, cost and justification problems. Thus the cell approach to unattended machining is seen as the way forward. It can be developed using a step-by-step build-up of the major elements and in such manner spreads the capital costs and hence risk, over a longer period.

2.3 Manufacturing System Design

2.3.1 Definition, Context and Significance

Manufacturing system design can be conceptualised as the mapping of performance requirements of a manufacturing system, as expressed by values of certain performance measures, onto suitable values of decision variables, which describe the physical design or the manner of operation of the manufacturing system [49]. Performance measures can either be benefit measures or cost measures, and are divided into four major categories: cost, quality, delivery, and flexibility. These gross measures can be further broken down into more specific performance indicators. In general, a number of performance measures will be relevant for a given manufacturing system. However, these will differ from one manufacturing system to another. Wemmerlov & Hyer [283] suggest the separation of system design activities into those related to system structure and those related to system operation. In adopting this convention, in the context of the present work emphasis will be on the structural design, as opposed to operational design.

The manufacturing system design function is primarily responsible for the provision of resources for the operations function. It is also responsible in conjunction with the management information system (MIS) function for the company-wide provision of resources for product design and marketing, as shown schematically in Figure 2.8 [195]. This conceptual representation of the manufacturing system design function within the manufacturing enterprise is consistent with the notion of the manufacturing system being part of the production system as proposed by Black [26], and discussed in Section 2.2. Also shown in Figure 2.8 are the considerable interactions and interdependence between manufacturing system design function and other functions within the manufacturing system, as well as those outside the system such as the customer and the systems suppliers.

Typical reasons why manufacturing systems need to be designed or redesigned include:

- new product development due either to a change of model, or to fulfil new order,

* the need to increase capacity in excess of the present system,
* the need to replace plant or a section of the plant due to obsolescence,
* to improve the performance of the current system, and
* to meet some or all of the business objectives.

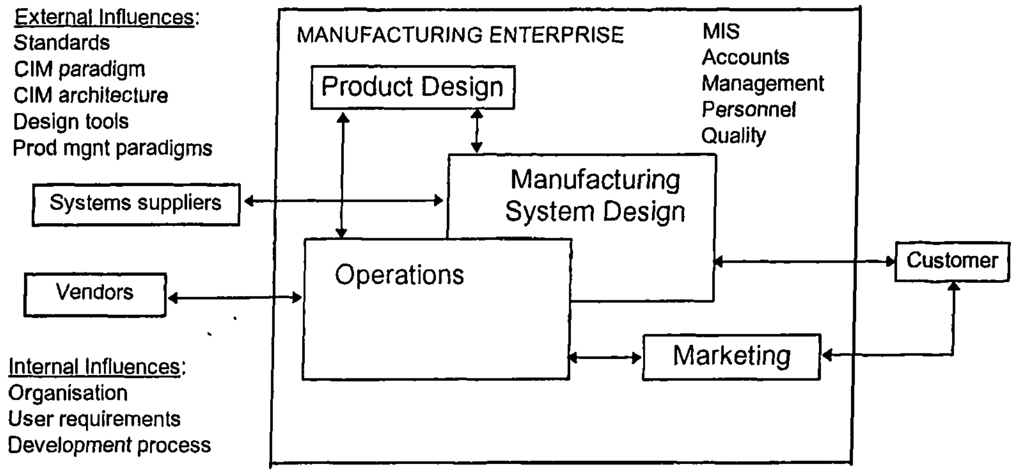


Figure 2.8 The context of manufacturing system design [195]

The significance of manufacturing system design tasks is determined by its impact upon the operating efficiency of the manufacturing system, as evident in Figure 2.9 [57]. The greatest impact on project cost and operating efficiency occurs during the initial project planning phase. Although commitment of corporate resources increase later in the design phase, as equipment is purchased and the implementation begins, the level of resources required for the construction and on-going operational costs depend on the accuracy of the decisions made during the planning phase. This shows evidence of the importance of the manufacturing system design process. Furthermore, it has been stated, for example in [116] that the production function is responsible for one third of the total product cost. Although small when compared to the influence of product design on cost (70%), effective design of the manufacturing system can contribute to the overall efficiency and the economical manufacturing activities.

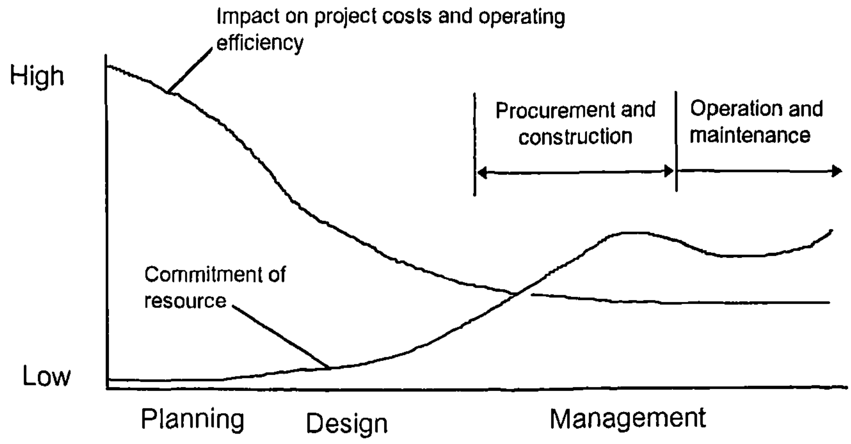


Figure 2.9 Impact of planning and design on manufacturing systems [57]

2.3.2 Manufacturing System Design Problems

The decisions required in the structural design of a manufacturing system include selection of part types and the quantity to be manufactured; selection of production system(s) used to produce the required products; selection of the equipment for the production system, which include selection of the machining system, defining the number of load/unload stations, selection of material handling and tool handling systems, and defining the number of tools, fixtures and pallets needed; defining the layout of the system; and defining the number and skills of personnel needed. In the context of advanced manufacturing, decisions are also required on the information control system such as the determination of computer hardware and software, communication and networking systems, and the integration of all these elements. A number of literature provide a good description of the system design problems [26, 28, 49, 53, 89, 154, 162, 256, 265, 283, 295],

Selection of Manufacturing System

In the system selection process, initial economic justifications and feasibility study form the major tasks [260]. Feasibility study and economic analysis are used to establish the economic justification of various potential system alternatives that are candidates for targeted product designs. Problems addressed include determination of system objectives, assessment of candidate products, selection of subassemblies and whether components are to be made or ordered, impact of alternative product designs on the manufacturing process and system configuration, implication of alternative process approaches, selection of candidate equipment, the decision of process flexibility, and determination of system constraints imposed by capital investment or strategic requirements.

Techniques that are appropriate for initial economic justification and feasibility study include market and technological forecasting, economic analysis for alternative systems (for example discounted cash flow method and cost and benefit analysis) [41, 200], multi-criteria decision models [146], scoring methods [261], strategic investment planning [289] and integer programming [228, 284].

Machine Cell Formation

In this design problem, also known as part-machine grouping or group technology problem, parts with similar machining requirements are grouped into part-families and machines capable of processing one or more part families are organised into cells. The design objective is to minimise the total number of intercell moves made by the parts between manufacturing cells. There are two principal approaches to the problem. Production flow analysis, due to Burbidge [38], forms part families and the associated machine cells by analysis of the data in routings. Another approach is machine-component group analysis which forms the machine-component groups by permutation in rows and columns of the machine-component chart. The techniques used include algorithm such as rank order clustering, mathematical programming, graphic theoretic approach, genetic algorithm, heuristic approach, expert system and neural network. Detailed reviews of the machine cell formation problem are available in a number of literature [46, 100, 140, 152, 167, 236, 282].

Equipment Selection

As an integral part of the whole process of manufacturing systems design the equipment selection process is used to determine the components of a selected system, which include the machine tools, material handling system, and the associated control systems. Design problems addressed include translation of corporate product requirements into individual task for equipment selection in the system, determination of processing capacities and equipment reliability, and requirements of material handling and storage. The selection of manufacturing equipment for advanced manufacturing systems is of considerable importance for a manufacturing company, since it usually involves large capital investment. By selecting the right number and type of equipment a company can reduce the investment cost, reduce maintenance and operating costs, increase machine utilisation and improve the layout of equipment. A number of factors influence the selection process, such as part design, production rate, precision and the degree of flexibility required. Detail discussion of these factors is available in [104, 162, 266].

A number of methods, procedures and models have been developed to aid decision making in machine selection problem. Traditionally, selection techniques based on financial evaluation such as return on investment, payback, and cost-benefit analysis were more prominent as price was the only main concern. An early survey on non-financial approaches of equipment selection problem was conducted by Miller and Davis [182]. The increasing technical complexity and the integration issues of machines and equipment have increased the number of factors for consideration. More non-financial techniques are being used. These include scoring models [29], non-linear cost minimisation [18], weighted average rating procedure [167], knowledge-based system [154], and multiple criteria decision analysis [3, 9, 188]. In the area of robot selection problem, Khouja & Offodile [132] provide a comprehensive review on the methodologies that have been developed.

Facility Layout

Facility or resource layout problem is concerned with the placement of production facilities on the factory floor so that a set of production requirements are met. These include [87] minimising overall production time and cost, minimising material handling time and cost, minimising variation in types of material handling equipment, minimising investment in equipment, maximising effective utilisation of existing space, and maintaining flexibility of arrangement and operation. The pattern of layout is basically decided by the relationship between the number of product (P), and production quantity (Q). There are three basic layouts: product (or flowline or production line) layout for high Q/P ratio, process (or functional) layout for low Q/P ratio, and group technology (or cellular) layout for medium Q/P ratio.

The facility layout problem has been formulated in a number of ways such as the template shuffling formulation, the quadratic assignment problem, and the relationship chart formulation. Detail description of these formulations is given in [49, 87]. Recent surveys on facility layout problems are given in [155, 161].

2.3.3 Design Objectives

In order to conform to the argument that manufacturing assumes a strategic role in the achievement of corporate objectives [113], the design solutions must be supportive of the company's overall manufacturing strategy. Further, it can be deduced that the objectives of manufacturing systems design can be categorised in a hierarchy from strategic, tactical and to the operational level. At each level the major task of designing is to fulfil the pertinent objectives by mapping decision variables onto appropriate performance requirement. The relationship between the manufacturing strategy and manufacturing system design is discussed in Section 2.5.

At the tactical and operational level of a given system, the design process are to fulfil most of the following objectives, which are normally expresses in terms of some performance measures.

- Throughput - the ability to produce the number of parts needed.
- Flexibility - the ability to produce the variety of parts needed and/or to accommodate changes in part design or part mix.
- Quality - the ability to produce parts conforming to design requirements.
- Flow time - the ability to produce parts needed in as short a time as possible.
- Utilisation - the ability to keep system resources producing products as much of the available time as possible.

- Inventory - the ability to minimise the work-in-progress and finished goods inventory levels while still allowing the system to function smoothly.
- Economic efficiency - the ability to produce the mix and volume of parts required at the lowest total cost per part.

Unfortunately the above objectives are often in conflict with each other. For example, increasing flexibility may jeorpadise utilisation and economic efficiency as accommodation of flexibility means the need for more set-ups and changeovers. High machine utilisation requires considerable stocks of work-in-progress so that there are always jobs waiting to go on the machine. Parts with long set-up times should be made in large batches to reduce total setting-up time. However these steps would result in high investment in stocks. Thus, the approach to the design and specification of manufacturing systems must address these conflicting needs. Another observation from the above list is that, manufacturing firms need to comply with two sets of objectives linked by a strong duality, external *objective of the market* and *internal objective of production*. Bruyand et al. [37] consider this duality as the heart of the problematic of product design and it supposes a systemic approach of the firm and an integration of its main functions. Similar observations, if not more complex, can be said of the design of manufacturing systems.

2.3.4 The Influencing Factors

As indicated in the last section, the design function of manufacturing system is influenced by internal and external factors. At the strategic level design decisions must reflect the manufacturing system's response to the market and competitive demands. This will be discussed in greater detail in Section 2.5. This section will review some of the factors that affect the choices related to the technology selection and the overall configuration of the manufacturing systems. These include product mix characteristics, technology alternatives, cost parameters, product demands and length of planning horizon [162]. These factors normally act as the constraining elements in the system design process.

Product Design

The size and shape of the workpiece determine the types and sequence of processing. This will affect the selection of machines and the material handling equipment as well as the part set-up in the system. The level of accuracy required by the individual part also have strong influence on the type and precision parameters of the production equipment. The techniques such as simultaneous engineering and design for manufacture have been developed to ensure the maximum compatibility between product design and the processing requirements.

Product Mix

The range of products that can be manufactured by a manufacturing system is a function of the technology used. It also determines the complexity of the planning problem. A stable product mix, either a single product, or several variants of a basic product allows aggregation of all variants into a single product family. However a changing product mix can affect the performance of the manufacturing system. It has been shown for example that as the number of product mix is increased, the optimal lot sizes of production and queuing delays increase [130]. If a diverse and dynamic product mix is to be produced, evaluation of factors such as operational flexibility and cost of alternative technologies becomes more difficult.

Product Demand

Product demand, which may be characterised along several dimensions, as shown in Figure 2.10 [162], is an important factor that determines investment levels and systems capacity requirements. In situations where demands are assumed to be given, the objective is to develop medium or long-term plans to meet the demand. In more complex situations, the demand levels are treated as decision variables to be determined in conjunction with choices related to production facilities. The use of stochastic demand models in this case is necessary so as to utilise the flexibility benefits afforded by the integrative technologies such as CIM and FMS.

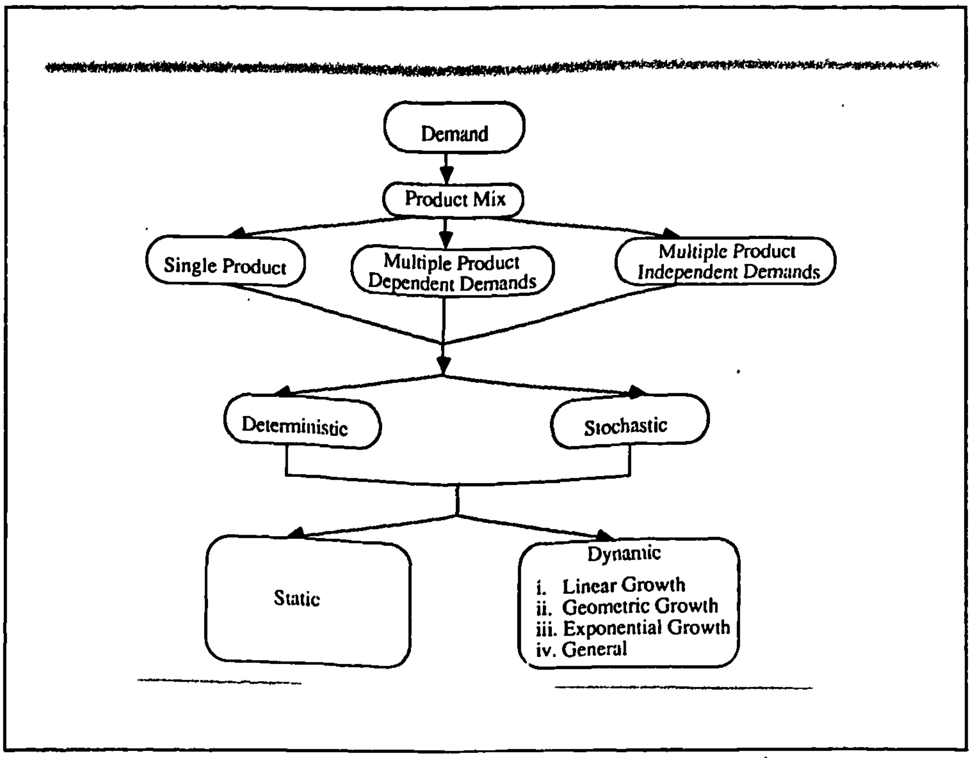


Figure 2.10 Multidimensional attributes of demand [162]

Another aspect of product demand that has significant impact on the design of manufacturing systems is that related to the product life cycle. The product life cycle is normally described in the following phases:

- *Start-up*. New product or new company, low volume, small company.
- *Rapid growth*. Products become standardised and volume increases rapidly. Company's ability to meet demand stresses its capacity.
- *Maturation*. Standard design emerges. Process development is very important.
- *Decline*. Product is slowly replaced by improved products.

As the competition shifts during the different stages of the product life cycle, the requirements placed on manufacturing system - cost, quality, flexibility and delivery also change. The maturation of a product in the market place generally leads to fewer competitors, with competition based more on price and on-time delivery than unique product features. The stages of the product life cycle affects the product design stability, the length of product development cycle, the frequency of product design changes, and the commonality of components. These will have implications on the manufacturing processes and system. The different designs of manufacturing systems reflect the ability of the company to manufacture at various volumes while decreasing the unit cost over time. Thus synonymous with product life cycle is that of manufacturing system life cycle [70, 78, 105, 160, 260]. Each and different stages need distinct analysis. However the major motivation is to create manufacturing systems that spans several product life cycles.

Technology Choice

The choice of appropriate technology is an important decision because it involves a large amount of capital and can have fundamental effects on the competitiveness of the firm. The development of automation and computer controlled equipment has facilitated the production of a variety of products. In batch manufacturing, automation is taking place at three levels of sophistication: stand-alone machining and turning centres, clusters of machines grouped into cells, and flexible manufacturing systems which can produce families of parts in random order, unattended and with little intervention. Furthermore these modern technologies permit improvement in quality and cost reduction.

Cost Function

Cost is one of the important factors in technology selection for manufacturing system design. Investment in advanced manufacturing has to be justified in economic terms. During the budgeting process, a clear distinction has to be made between the resources needed to support current operations and the incremental resources needed to implement integrated manufacturing [91]. For engineering and fabrication industries a fixed charge cost function has been proposed to describe the cost characteristics of the production technologies used, where capacity increase is in small increments [162]:

$$f(x) = \{^{0}_{F+vx} \quad \text{if } x \geq 0.$$

In the above equation, $f(x)$ is the cost function, x the amount of capacity addition ($x \geq 0$), and F and v are the fixed and variable costs in investment respectively. In a model of capital costing [183] it is suggested that capital costing must begin with an overview of the entire factory, followed by the specific work cells, which are then linked to individual equipment units.

Planning Horizon

Technology and equipment selection is a long-term decision with the length of the planning horizon depending on many factors that include maturity of technology, level of investment, uncertainties in demands, cost, and dynamics of product mix. The investments required have to be justified over a period of several years. A plan which addresses both short- and long-term goals is needed and it must be justified in term of improved products and processes [91]. Discrete time and finite horizon models that explicitly consider the alternatives are required to describe the relevant trade-offs.

2.3.5 Restrictions and Problems

Modern manufacturing systems are often complex, consisting of many interconnected hardware and software. An estimated 50-75% of projects of this nature fail to meet the expectations regarding cost, start-up dates and subsequent performance [122]. Besides having to balance the conflicting needs of the manufacturing system, there are other issues that make designing manufacturing systems a difficult task as discussed by various authors [49, 195, 260].

Suri [260] outlines the difficulty of decision making in a complex modern manufacturing systems as due to: (1) Highly interconnected components leading to a very large set of decisions that must be made simultaneously. (2) Limited resources due to efficiency requirements. (3) The reduction of 'slack' in the system. (4) The shortage of human operators results in the unexpected perturbations of the system not being corrected in time.

In discussing the different scenario between academic research and industrial practice, Chryssolouris [49] outlines the following limitations to manufacturing system design:

(1) Manufacturing systems are large and have many interacting components; (2) Manufacturing systems are dynamic; (3) Manufacturing systems are open systems which influence and are influenced by their environment; (4) The relationships between design objectives and the decision variables usually cannot be expressed analytically; (5) Data may be difficult to measure in a harsh processing environment; and (6) There are usually multiple objectives or performance requirements for a manufacturing system and these may conflict.

O'Sullivan [195] lists some of the reasons for the failure of manufacturing system design implementation that include: (1) The equipment-supplier relationship; (2) The fit between the company's products and the production processes; (3) The fit of the manufacturing processes and the company's manufacturing strategy; (4) The education and training of personnel; (5) The integration with other support systems; (6) The commitment and support of top management; (7) The pace of adoption; (8) The amount of work subcontracted; and (9) Relative infrequency and high cost of this type of project.

Reasons 1 to 8, while important, can and should be improved through the normal learning process if projects are frequently implemented. But generally, this type of project is not frequently implemented, and so the necessary experience for these costly and resource-intensive efforts cannot be developed in the normal way. Companies faced with having to improve their systems find themselves thrown into environments which are highly complex, with little project implementation experience, and under tremendous pressure to get things done right first time, due to costs involved and changes within the systems which will arise. In addition the manufacturing system design process is also faced with a number of challenges such as keeping the solution simple and 'requirements driven'; involving the ultimate user in the design process; designing for automation; and maintaining long term focus while being responsive to the short term needs.

Faced with these challenges, the manufacturing systems design process has to develop a new approach to learning and developing internal expertise in this area. This has to be coupled with new tools and methodologies which facilitate the design efforts in developing integrated systems.

2.4 Methodologies and Tools for Manufacturing System Design

2.4.1 Introduction

It was shown in the last section that a manufacturing system is a very complex network of physical entities and activities, decision making and information flows. The fundamental activity in design is decision making, and the design of manufacturing systems involves the process of deciding the values of decision variables of the manufacturing system. The increase in the level of automation in advanced manufacturing systems which may culminate in computer integrated manufacturing (CIM) also means that the number and complexity of decision variables increases. Hence a methodology is needed for guiding the designer towards an efficient and realistic system design. The issues of integrating the design, manufacturing and management functions need to be addressed. A poorly designed system would adversely affect the operations of the system such as planning, scheduling, production control and quality control.

The purpose of this section is to provide a review of the various methodologies and approaches that have been developed for the design of manufacturing systems. The methodologies will be grouped under several categories, namely, manufacturing systems engineering analysis, axiomatic approach, structured methodology, strategic and organisational approach, operations research approach, artificial intelligence and other approaches. The classification is not exclusive as some tools are used in more than one methodology.

2.4.2 Manufacturing Systems Engineering Analysis

A methodology based on five basic stages of designing manufacturing systems and a study of international corporate best practices has been developed at Lucas [7, 60, 202-204]. These basic stages which reflect the essence of systems approach to manufacturing system design and redesign were initially proposed by Parnaby [201]. They are:

- Data collection on markets, products, process flowcharts and machine capabilities. search for patterns and natural cellular architectures.
- Steady-state design based on subsystem input/output analysis to define basic configurations of cells, machines, processes and people and their matching interface requirements.
- Dynamic design to account for areas of potential change, e.g. in product mix.
- Information flow system and databases definitions.
- Control function definition, control system design and overall control systems integration for day to day operations management.

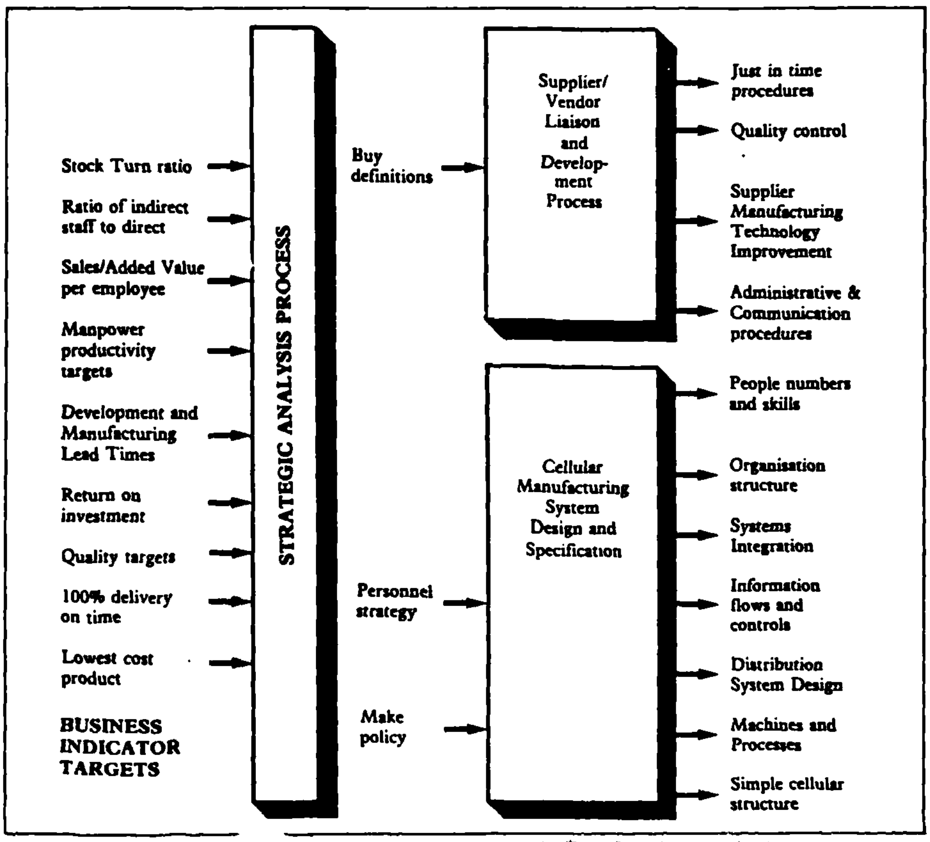


Figure 2.11 Summary of Manufacturing Systems Engineering Approach [202]

The manufacturing systems engineering approach seeks to tackle the design problem based on quantified statement of business objectives. Figure 2.11 shows a summary of the methodology. The methodology has been adopted in the restructuring of a number of Lucas business units and improvements in performance have been reported [60]. The methodology is implemented by the setting up of task forces comprising of personnel with experience and skills across the business unit. It can help the business units or firms understand the fundamental issues and resolve the systems complexity.

2.4.3 The Axiomatic Approach

The application of axiomatic approach to manufacturing system design rests on the premise that the purpose of designing a manufacturing system is to create a set of physical entities that satisfies the specified functional requirements with the least expenditure of resources in the form of materials, information, labour, and capital [257]. This goal is accomplished when design decisions are made rationally at every step of the decision making process. This can be done most effectively using the design axioms that govern good designs. By definition, axioms are fundamental truths that are always observed to be valid and for which there are no counter examples or expressions. Corollaries are a direct consequence of one or more of these axioms. From these axioms and corollaries, theorems can be derived for making design decisions. There are two axioms that govern good design practice [257]:
Axiom 1: Maintain the independence of functional requirements. In an acceptable design, the design parameters and functional requirements (FR) are related so that each functional requirement is satisfied independently without affecting other functional requirements.
Axiom 2: Minimise the information content. The best design is a functionally uncoupled design that has the minimum information content (less complex).

The corollaries have been found to be more useful and readily applied to actual design situations. Sometimes called design rules, these corollaries are:

- *Decoupling of coupled design.* Decouple or separate parts of a solution if the FRs are coupled or become interdependent in the proposed designs.
- *Minimisation of FRs.* Minimise the number of FRs and constraints. This corollary recommends the designer to strive for maximum simplicity in the overall design.

- *Integration of the physical parts.* Integrate design features into a single process, device or system when FRs can be independently satisfied in the proposed solution.
- *Use of standardisation.* Use standardised or interchangeable processes and operations if the use of these elements is consistent with functional requirements and constraints.
- *Use of symmetry.* Use symmetric shapes and/or arrangements if they are consistent with functional requirements and constraints.
- *Uncoupled design with less information.* Seek uncoupled design that requires less information than coupled designs in satisfying a set of FRs.

Examples have been described on the applications of this approach in the design of linked manufacturing cells [26, 257] and the design of manufacturing system at Honda Motor Company manufacturing plant [27]. The disadvantage of this approach is that it is limited to focusing internal requirements rather than addressing the more important external customer demands.

2.4.4 Structured Methodology

One way of analysing a complex system is through the use of structured methods. The structured methodology is based on system modelling techniques in which the operations and activities that occur within the complex manufacturing systems can be represented graphically. The aim of using structured methods is to anticipate and solve during the design stage every possible problem encountered throughout the life cycle of a manufacturing system. The real system is described by a concise, multilayered and structured model, which will in turn be mapped into computer memory as a design aid, as shown in Figure 2.12. The methodology was initially developed for the design and implementation of large data processing systems.

The structured methodology has two inherent properties: *Communication*, which aims to model exchanges of information or physical items between system activities, and *Synchronisation*, which models activity links and relationships between links and outside events. The philosophy behind structured techniques is that systems can be disassembled into smaller elements, i.e. top-down analysis, allowing the whole problem to be seen at the same time as its more detailed constituent parts. The use of structured methods in the design of manufacturing systems is supported by conceptual models which are collection of concepts representing the schema of the system.

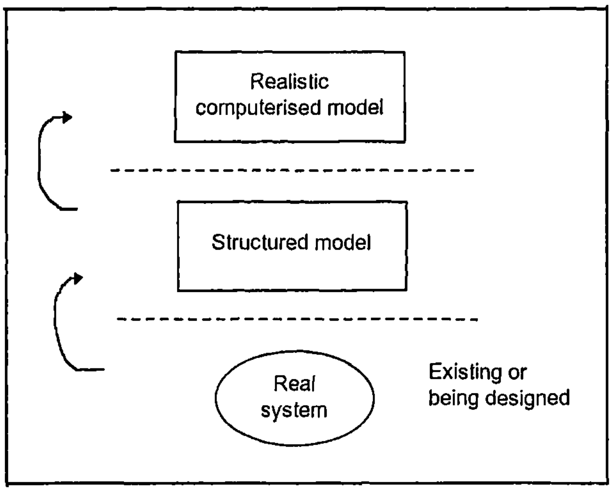


Figure 2.12 Different levels of modelling for design [68]

The schema is the image of the actual system and it provides a notation for representing the manufacturing operations. Such schema or notations ensure standard ways of representing relationships between activities and flows of data. This is important as it ensures common understanding of systems and to provide results of analysis which are reproducible and comparable. A brief review of some of the techniques involved in the structured methodology follows.

2.4.4.1 SADT

The Structured Analysis and Design Technique (SADT) is a system development methodology which was initially developed for the computer software development [221, 222]. It is divided into several phases - analysis, design, implementation, integration, testing, installation, and operation [171]. This technique is useful in the analysis and design phases of the information system development for manufacturing systems.

The tools that are used for system modelling are activity diagrams and data diagrams. These are utilised in a top-down manner, starting with a single function and decomposing this in order to obtain the necessary level of detail. The activity (and data) diagrams shows the function which occurs, together with their inputs, outputs and controls.

2.4.4.2 IDEF Methodology

IDEF (ICAM Definition) language is an approach in modelling the complex and interrelated sub-systems and functions in a manufacturing system based on ICAM (Integrated Computer Aided Manufacturing) conceptual model. IDEF was developed by the US Air Force in the early eighties to describe the information and organisation structure of complex manufacturing systems. The methodology is similar to that of SADT (Structured Analysis and Design Technique) described earlier. The ICAM conceptual model is a top-down approach of modelling the whole organisation as a collection of sub-systems of inputs and outputs, and then modelling each of these sub-systems as a further collection of sub-systems. The conceptual model can be viewed in three perspectives: the factory view, which is a multi-product and company dependent view of manufacturing; the composite view, which is based on the essential decisions, actions and activities required to produce a product; and the generic view, which synthesises the information contained in the composite view. It shows all aspects of the manufacturing function in a single model, and this is the focus of ICAM system and module development.

$IDEF_0$ is used to produce functional models which describe the static structural relationships of the functions and entities within a manufacturing system. The modelling technique highlights deficiencies in the organisation and makes it easier to understand the detail working of a company. The basic element of an $IDEF_0$ model is called a function block, Figure 2.13. In this model, the individual function blocks are linked together through inputs, the outputs, the mechanism and the controls. When an input is utilised to create an output, a function will be actuated. The performance of the function is carried out through a mechanism and under the guidance of the control. A function block in the system can be decomposed into more detailed function blocks further down the structure hierarchy as shown in Figure 2.14. The highest-level function block describes the main purpose of the subject system and the lower-level function blocks describe the supporting sub-systems which exist to serve the upper levels. As a rule a function at a given level can only be decomposed into between three and six sub-functions at the next level. The use of IDEF methodology in the planning and design of manufacturing systems has been reported in the literature [15, 169, 170, 216, 229, 275, 295, 297].

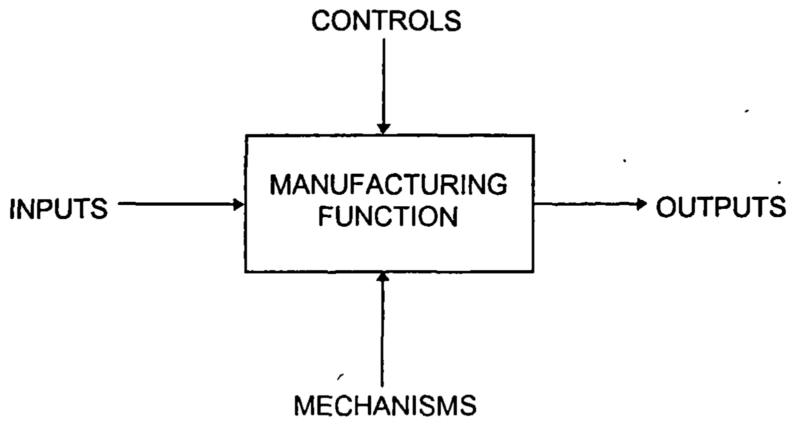


Figure 2.13 $IDEF_0$ function block

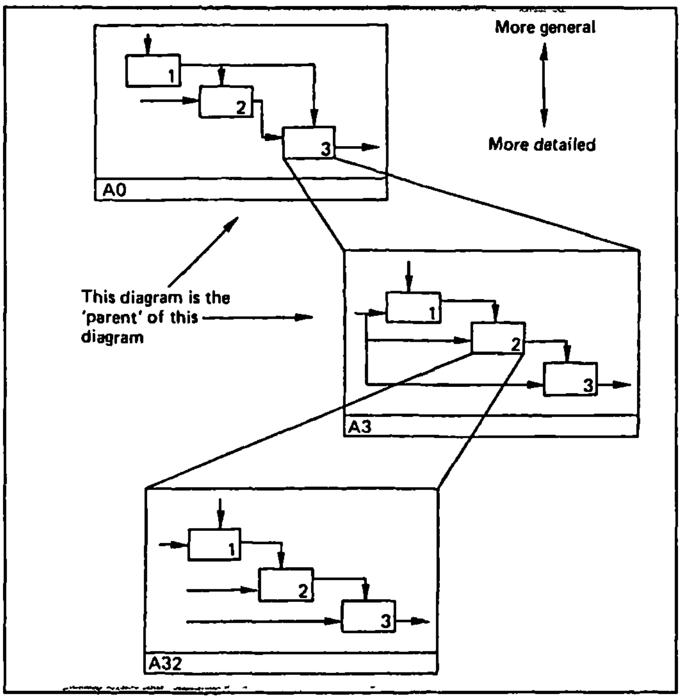


Figure 2.14 $IDEF_0$ decomposition.

The extension of the technique results in two additional basic levels: $IDEF_1$ (which includes $IDEF_{1x}$), and $IDEF_2$. $IDEF_1$ is used to describe the relationships between data items in the environment such that a relational data base model to support IDEF0 may be specified. The $IDEF_1$ diagram consists of a number of entity classes for a particular function or activity that are connected by lines and symbols to represent the relationships between them. $IDEF_{1x}$ specifically addresses the logical structure of shared data, defining this structure in terms of entities, attributes of entities and relationships between entities. $IDEF_2$ is a simulation technique that can be used to investigate the system's dynamic behaviour over time so that expected performance can be measured and decision criteria can be established. These three techniques may be used independently or in any combination of models, to form an 'architecture' when the environment of the system being modelled is comprised of component systems, organisation and/or technologies working together to accomplish the overall objectives. Further development of the IDEF versions has also been reported in [174], and is shown in Table 2.3.

IDEF Versions	Brief Description
$IDEF_3$	Used to capture domain expert knowledge about the behavioural aspect of existing and proposed system.
$IDEF_4$	Used as a design method which utilises object-oriented paradigm. rather than relational approach, i.e., IDEF1x.
$IDEF_5$	Defined as an ontology modelling approach, it is used to describe the concepts and conceptual relations for a system.
$IDEF_6$	Attempts to capture the logic underlying the decisions contributing to, or resulting in, the final design of the system.

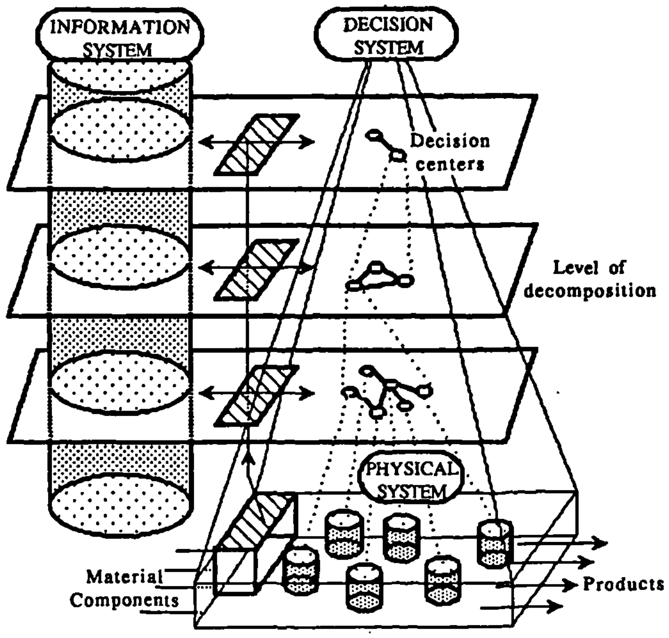
Table 2.3 Developments in IDEF methodology [174].

The IDEF technique has the advantage of providing an effective communication medium for system designers to understand the functional and information structure within a complex manufacturing system. The different parts of the total system can be analysed simultaneously and independently as they can be decomposed readily. Its 'top-down' nature ensures that the analysis of one level is not commenced until the previous level is completely described, thus allowing the system to be studied to any level of details as desired. The limitations of $IDEF_0$ are in terms of the learning time involved, cumbersome, ambiguity of function specification and its static nature. The construction of a complete $IDEF_0$ model of a system is an iterative process as the data presented in the model should be consistent with the actual system. The static modelling precludes the representation of the conditions or sequence of processing in the model itself.

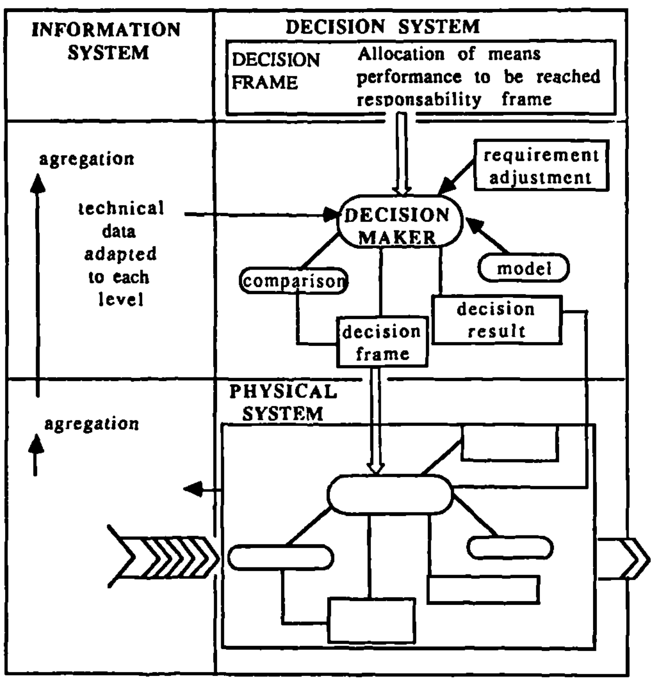
2.4.4.3 GRAI Methodology

The GRAI (Graphe à Resultats et Activites Interlies) methodology has been developed for the analysis, design and specification of production management systems [68-70, 212]. The GRAI model conceptualises the structure of manufacturing systems as consisting of two parts: the physical system and the production control system. The input to the control system is information about orders, resources, energy, etc. The inputs to the physical system are parts and components, the output being the product. The production control provides instructions to the physical system, which in turn passes information to production control. The decision system and the information system form the elements of the production control system. Figure 2.15 shows the GRAI conceptual model which is made up of two parts, the structure of production control system and the structure of a decision system. As a set of design and analysis rules, both models represent various concepts allowing a consistent, valid and adapted representation to be drawn up.

Two graphic tools are used in GRAI methodology: GRAIgrids and GRAInets. The GRAIgrid (Figure 2.16) aids in the analysis of the production management system and is concerned with the control systems in the manufacturing organisation. The tool uses a top-down approach to identify what decision centres are required to achieve a co-ordinated system. The GRAIgrid matrix consists of a standard set of functions in the columns and the desired time decision time-scales in the rows. Each square in the matrix is considered to be a potential decision centre in the related function and time-scale. These are then examined in the context of the desired system, so as to establish whether there is indeed a set of decisions to be made in this response period.



(a) Structure of a production control system



(b) Structure of a decision system

Figure 2.15 GRAI conceptual model [68]

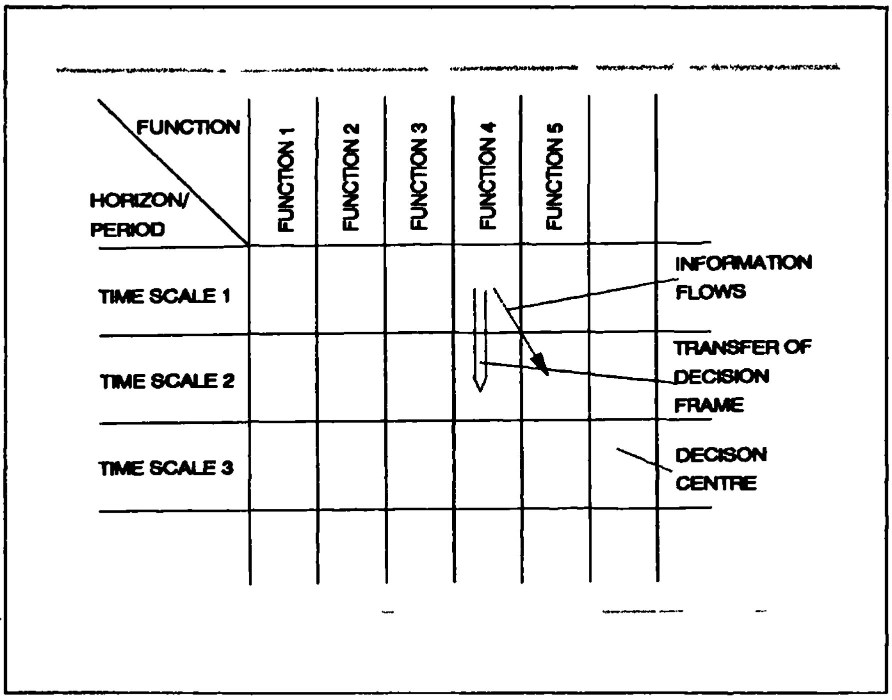


Figure 2.16 GRAIgrid [68]

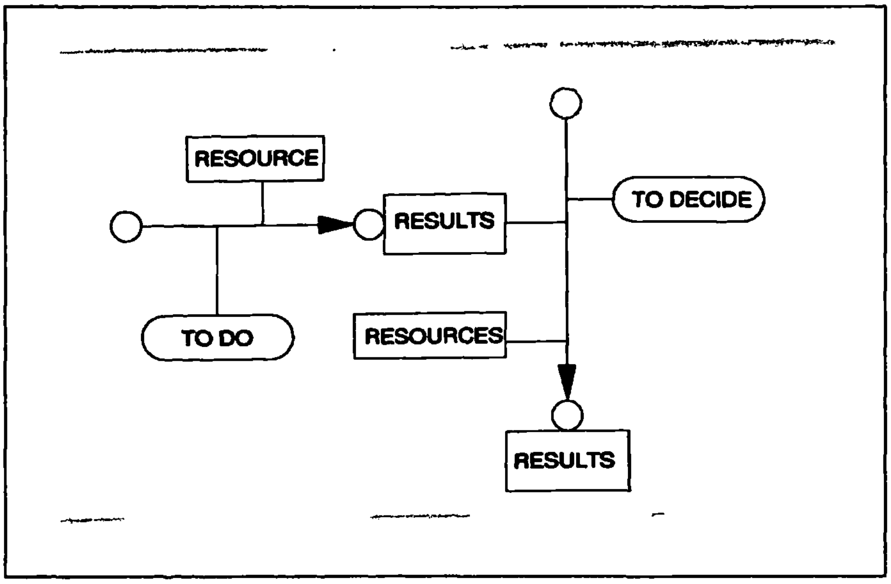


Figure 2.17 GRAInet [68]

GRAInet is a bottom-up approach used to describe the actual activities involved in each decision centre, Figure 2.17. The arrows together with their associated circles are used to represent the activities to be carried out. These can be either decisional activities (vertical) or process activities (horizontal). The resources and information requirements of the activities are specified in the rectangles. A GRAInet is developed for each decision centre which is identified as being necessary through the GRAIgrid analysis.

The application of GRAI methodology in FMS design recognises the existence of manufacturing system life cycle: analysis, design specification, development, implementation, and operation. The GRAI method for the design of physical system in connection with the decisional system is called GRAIFLEX [70]. It has been developed to deal with the analysis and design specification. The objective of the methodology is to reduce errors in design and hence improving the overall system performance by formalising rules in the early phases of design.

The usefulness of GRAI methodology lies in the fact that its emphasis on the first two phases of manufacturing system design has significant impact on the potential of reducing total system cost. The approach, however, does not encourage the designer to check for technological, economical or financial feasibility as well as the company strategy during the design process. In addition, the use of GRAIgrid indicates the dependence of the approach on large, centralised computers.

2.4.4.3 SSADM

The Structured System Analysis and Design Method (SSADM) [11, 71] is a standard structured method used in computer system development projects undertaken by UK government departments. It has been used mainly in the field of designing commercial and administrative information systems. It is made up of an integrated set of structural, procedural and documentation standards. The structural standards break the development into six stages, each stage consisting of a number of steps. For each step procedural standards define how the step is to be implemented, and documentation standards define how the products of the stage are to be documented. Figure 2.18 shows an outline of the SSADM structure.

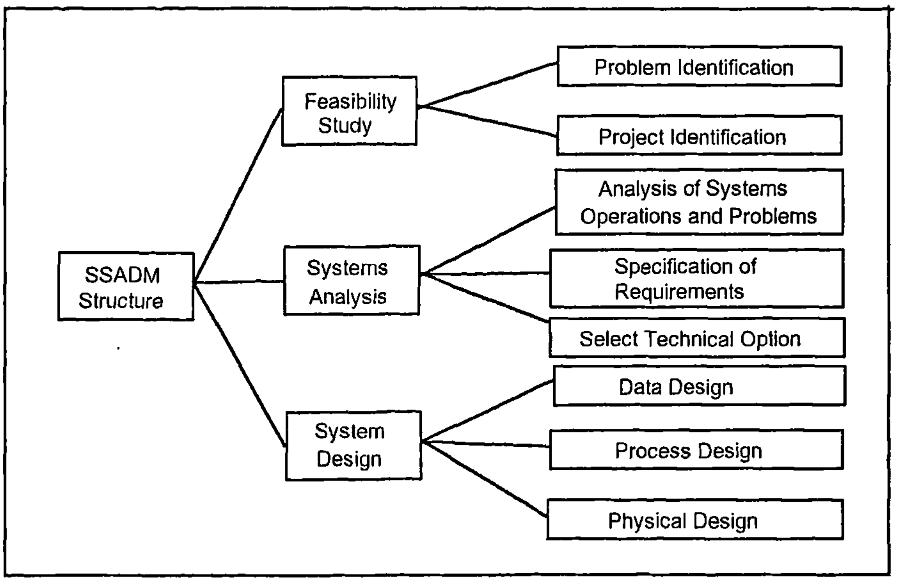


Figure 2.18 SSADM structure [71]

The tools used in the SSADM are:

- Data flow diagram (DFD). It is a method of representing the flows of information through a system and between the system and the external environment.
- Logical data structure (LDS). A method for describing what information should be held by the system. It is an entity modelling technique.
- Entity life histories (ELH). Models how the system's data is changed over a period of time by events.
- Relational data analysis (RDA). It is used in the structuring of data.

The relevance of SSADM in manufacturing systems design is due to its inherent comprehensiveness in the development of software, data processing and data storage. This capability is important in the later phases of manufacturing system design during which communications and information networks need to be designed. An example of top-level DFD representing the manufacturing environment as described in [170] is shown in Figure 2.19. The rectangles represent processes, the ovals represent external entities, the open-ended rectangles represent datastores and the arrows represent dataflows. Hence, if process #3 is considered, data in the form of part design, part programs and detailed schedules and plans are inputted for the physical production of the parts. Production and statistical information are then provided to other departments. Each of the three processes could be expanded into lower level of abstraction. The term 'external' entities is thus referring to departments outside the manufacturing system, but within the same company. This is consistent with the model discussed in Section 2.2.2 and shown in Figure 2.2.

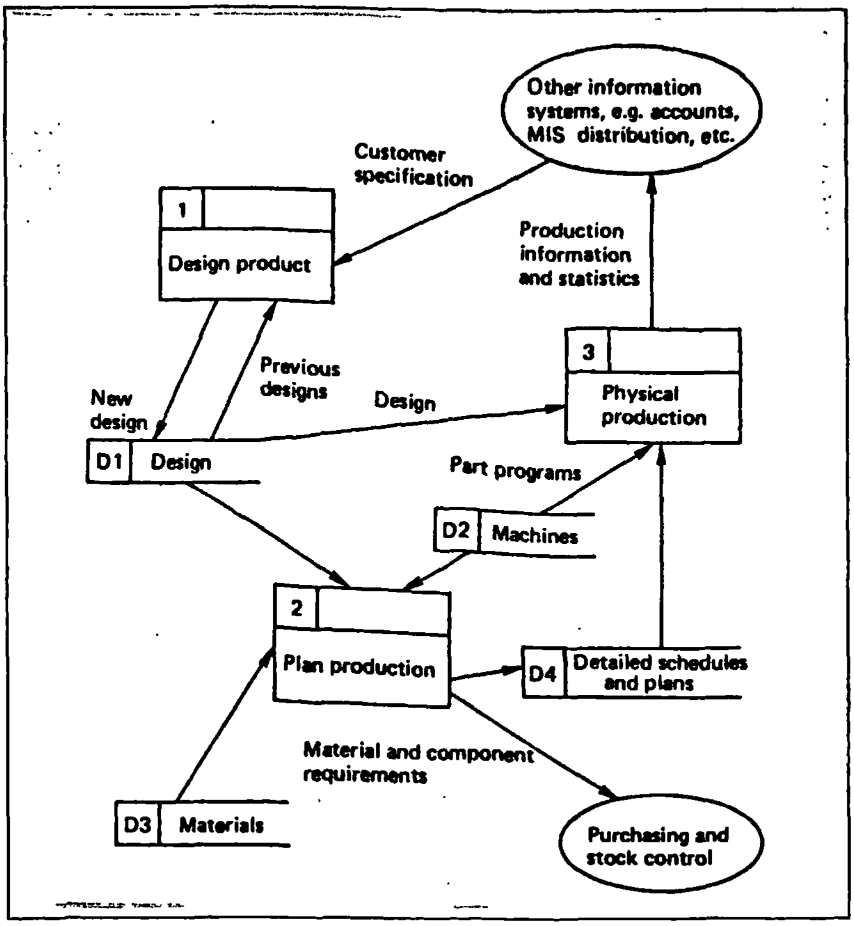


Figure 2.19 Data flow diagram of a general manufacturing environment [170]

Comments on Structured Methodologies

The higher degree of adoption of techniques such as SADT, SSADM and $IDEF_0$ is attributed to their being more commonly known to the manufacturing community. The similarity that exists at the analysis and design stages between software development and manufacturing system design makes the techniques easily adaptable for manufacturing system design. The decompositional characteristics of these techniques allow the analysis of complex and interrelated systems to be made. Structured methodologies can provide a systematic and methodical analysis of the system. The tools combine tasks and material flows to provide a complete physical model of the process. This will facilitate the study of the present system (as is analysis), should be and to be analysis. By formalising the design rules it provides a useful starting point in the systems approach to problem solving within the MSD.

The main reservation about their application is that they can often bring additional complexity to the project. This is due to the usage of a language 'foreign' to those in manufacturing, and reliance on relatively complex techniques. Being concerned only with functional, information and dynamic aspects of manufacturing operations, these techniques are divorced from the strategic aspects of the business. The richness of information contained in SADT and $IDEF_0$ models make it hard for users to appreciate it as a proper and correct model for their systems. The main assumption of these system modelling techniques is that each and every activity and managerial control can be represented by data. However it is not possible to produce a data representation of all aspects of manufacturing.

2.4.5 Strategy Related Methodologies

2.4.5.1 The DRAMA Decision Process Model

Design Routine for Adopting Modular Assembly (DRAMA) is a methodology based on the view that in modern manufacturing systems there is now greater tendency for operational process to be dictated by factors in the strategic and organisational domains [21, 22]. It makes use of a number of tools such as narratives, flowcharts, decision trees and checklists to lead a design and development process through the stages of decision-making in a concise and comprehensive manner. The methodology has been described as an empirical collection of guiding principles that allows companies to analyse their competitive position and thereby design a production system appropriate to their needs. It has three major domains:

- *Strategic*. Here the effects of decision processes are considered in relation to wider boundary-spanning activities, and in particular to the organisational and operational implications of environmental influences relating to co-operative, marketing and manufacturing strategies.

- *Organisational.* Factors which interrelate vertically are analysed in order to identify the variables which determine or are dependent on the different options within the strategic domain.
- *Operational.* Here factors that interrelate laterally within manufacturing are identified. This domain covers the physical design, implementation and operation of new systems.

The disaggregation of organisational decision-making into three domains supplements the longitudinal analysis provided the sequential components. Thus design activity and decision-making can be tracked at different levels of organisational analysis as well as laterally through time.

2.4.5.2 STRATAGEM

STRATAGEM is a systems methodology which has been developed for the design of integrated manufacturing systems with increased competitiveness [172, 173]. It is a top-down design approach which assess alternative solutions suitable for the company's regeneration process. The methodology consists of five principal stages: (1) Commitment, (2) Contracting, (3) Launch, (4) Application, and (5) Close. The application stage is further divided into four phases: strategic analysis, manufacturing analysis, manufacturing strategy and action planning. Rather than having specific tools, this methodology provides a guidance, through a framework for choosing the most appropriate tool(s) for a particular manufacturing environment.

2.4.6 The General Design Framework

Wu [295] describes a general design framework which has major emphasis on design and evaluation. In this methodology the current and the desired positions will be analysed prior to the setting of objectives. Based on the current position, constraints will be identified, which will produce realistic objectives. A new system will then be designed to fulfil these objectives. The structure of the approach is shown in Figure

2.20. The methodology makes use of the available tools such as data flow diagram, $IDEF_0$ and input-output diagram.

The first two stages of the general model, analysis of the situation and the formulation of objectives are in the category of manufacturing strategy. The conceptual modelling and detailed design stages represent the plan to transform the operation from the current to the future desired state. The conceptual modelling and detailed design stages are followed by evaluation of concepts and decision respectively. The rational decision on whether to implement the system will be based on two main criteria: (1) whether the system developed will meet the requirements set, and (2) whether the system will generate return to justify the investment. The approach is claimed to have positive results on manufacturing system design process by improving the quality of design produced, thus reducing the problems and costs associated with poor system specifications.

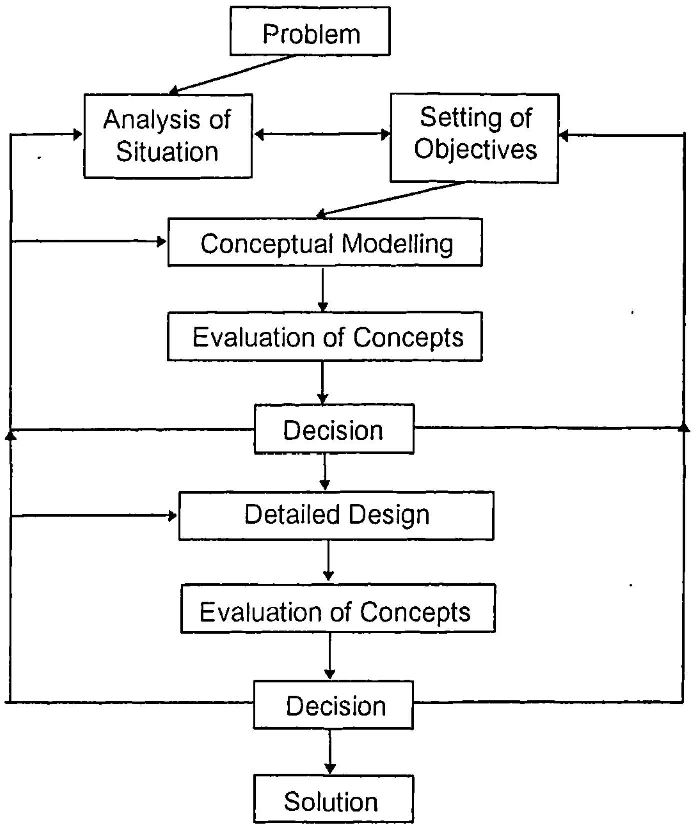


Figure 2.20 General Design Framework [295]

2.4.7 The Use of Modelling and Simulation

Computer simulation is an approach for studying dynamic behaviour of a system by experimenting with an appropriate computer model rather than with the real system itself. It has the advantages of lower cost, shorter time, greater flexibility and much lower risk. The use of modelling and simulation in planning for FMS is essential in evaluating the detailed specification and performance requirements. During part of this research work, the author has had the opportunity of participating in system evaluation project using computer simulation. WITNESS simulation package was used in the analysis of wire stranding operation with the objective of improving the productivity of the process. Detail description of the project is given in Appendix B.

In manufacturing systems engineering computer simulation is applied to two basic types of problems [295]: *system evaluation* in which an existing process is simulated to determine which is to be adapted or expanded according to the changing operating conditions, and *system design*, where new process is investigated to avoid pitfalls and to observe the reaction to extreme operating conditions. A comprehensive review of the modelling approach in flexible manufacturing system is provided by Kalkunte at al. [126]. A four level hierarchical framework is used to systematise the management decision related to the design, justification and operation of an FMS.

Shimizu [237] develops an integrated approach for modelling manufacturing systems. The approach utilises the integration of spreadsheets, queuing, simulation and animation models. The integrated modelling approach covers the entire process of designing manufacturing systems, from initial rough-cut analysis to final detailed designed. Pang and Khodabandehloo [196] present a general methodology for production reliability analysis of flexible manufacturing cells (FMCs) during the design and development stages. The FMC is first simulated using SIMAN simulation language. The output is then used for generating system reliability models and evaluation by event tree analysis.

The following characteristics of simulation contribute to its usefulness in manufacturing system design: performance of systems can be studied without building them, impact of different operational strategies can be studied without implementing them, impact of external uncontrollable events such as component failures can be studied without requiring them to occur, and time can be expanded or compressed to study phenomena otherwise too fast or too slow to observe.

2.4.8 The Use of Operations Research Techniques

Operations research (OR) is an approach to the solution of problems that is based on the development and application of quantitative techniques [8]. More specifically, theory and methodology in mathematics, statistics, and computing are adapted and applied to the identification, formulation, solution, validation, implementation and control of decision-making problems. The techniques that are used in solving OR problems include mathematical programming, dynamic programming, and queuing theory [34, 293].

Mathematical programming is a family of techniques for optimising (maximising or minimising) a given algebraic objective function of a number of decision variables. The decision variables may either be independent of one another, or they may be related through constraints. The techniques involved in mathematical programming include linear programming, goal programming, and integer programming.

Dynamic programming is a method for solving problems that can be viewed as multistage decision process. A multistage decision process is a process that can be separated into a number of sequential steps, or stages, which can be completed in one or more ways. The options for completing the stages are called decisions. A policy is a sequence of decisions, one for each stage of the process. The condition of the process at a given stage is called a state at that stage; each decision effects a transition from the current state to a state associated with the next stage. Many multistage decision processes have returns (cost or benefits) associated with each decision, and these returns may vary with both the stage and state of the process. The objective of analysing such processes is to determine policy, one that results in the best total return.

Queuing theory is the study of the behaviour of queuing systems through the formulation of analytical models. A queuing system is a set of customers, a set of servers, and an order whereby customers arrive and are processed. A queuing process consists of customers arriving at a service facility, then waiting in a line (queue) if all servers are busy, eventually receiving service, and finally departing from the facility.

OR and Manufacturing System Design

A review of the application of OR models and techniques in advanced manufacturing systems is given in [49, 152, 239, 268]. The techniques are found to be useful in three areas of system design such as economic justification, selection of parts to be manufactured and the selection of storage systems. Chryssouloris [49] discusses the application of OR techniques in manufacturing system design problems which have been categorised as resource requirements problems, material flow problems and buffer capacity problems. This is summarised in Figure 2.21.

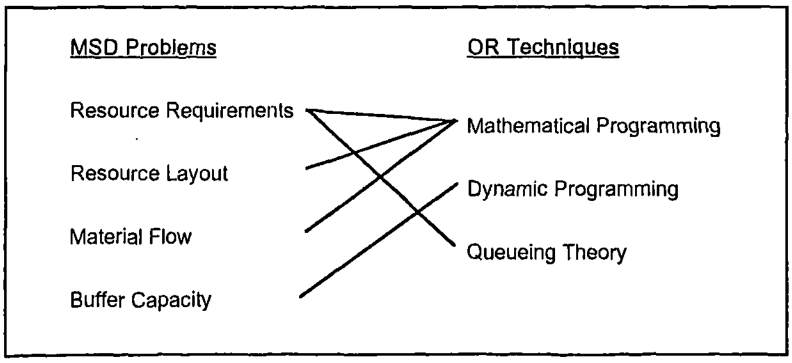


Figure 2.21 Summary of Applications of OR Techniques [49]

The significance of OR models in the design, operation and control of advanced manufacturing system is due to their ability to offer insights into the nature of interactions among components in such complex systems. The OR techniques whilst may solve complex manufacturing problems efficiently, are limited as the data for optimisation models may not be easily available. In addition the complexity of the algorithms may not provide optimal solution for industrial problems.

2.4.9 Artificial Intelligence

The goals of artificial intelligence (AI) are to make computers more useful, and to understand the principles that make intelligence possible. Two tools that make computers more useful in the design of manufacturing systems are *search* and *rule-based systems* [49].

In the search tool, if a manufacturing system design is assumed as a set of values of *n* decision variables, then any feasible design can be viewed as a point in an *n*-dimensional design space. A sensible design process must begin at an initial design point. From this point, a designer seeks to explore the design space, moving from point to point (design to design), evaluating each point as it arises. A sophisticated designer uses the information from previous evaluations (i.e. performance measures of the previously explored designs) to determine the path of future moves through the design space. In the end, the designer, having traced a path through the design space, will have arrived at the final design point, either because the optimal design point will have been reached, or because some limit on computational effort will have been exceeded. In either case, the objective is for the final design point to be superior to the initial design point, and describes a manufacturing system which meets the stated performance requirements.

Rule-based systems (also referred to as expert systems) are built around rules which consist of an *if* part and a *then* part [279] (i.e., if condition 1, condition 2, ... true, then take action 1, action 2, ...). A rule-based system consists of two major components: a *rule-base* and an *inference engine*. The rule-base is a collection of rules which captures human expertise or reasoning in a particular problem domain. The inference engine is a piece of software which invokes the rules in the rule-base to solve problems.

Another AI tool that is gaining popularity in manufacturing system design is the neural network [48]. A neural network consists of many non-linear computational elements operating in parallel and arranged in patterns resembling those of biological neurones. Computational elements, or nodes, are connected via weighted links, which are usually adapted in a learning or training process in order to improve performance. Inputs are supplied to the input nodes. From these nodes, the input values are propagated through the links to the other regions of the network. As they propagate, they are combined as they arrive at common nodes and changed according to the computational rules of the links and nodes through which they pass. Outputs from the output nodes form the numeric outputs of the neural network.

AI and Manufacturing System Design

Manufacturing systems problems which AI attempts to solve, are usually non-linear and combinatorially complex. Pankakoski et al. [197] discuss the use of case-based reasoning to manufacturing systems design. Chryssolouris [49] describes the use simulation and search approach in the design of automatic assembly system. In [48], neural network approach is used to learn the inverse of the simulation function: given the desired performance measure levels, the neural network outputs appropriate values for the system parameters.

Eloranta et al. [75] use knowledge engineering technology in the construction of a tool which aims to provide support during the process of MS design. Based on the 'controllability engineering' method, this knowledge- based system is directed towards the analysis and redesigning of manufacturing systems. The use of knowledge-based system for equipment selection, group technology problem for setting-up cell, and machine layout is described in Kusiak [154].

Pegler & Kochhar [208] describe a rule based approach to the steady-state analysis and design of JIT component manufacturing cells. The design methodology proceeds through four stages: (a) Gross load sizing, (b) Grouping by operation types, (c) Assessment of machine/people alternatives, and (d) Selection of machine/people alternatives. The steady-state or average values of the input variables to the cells such as product demand and machine capacities are used to arrive at the basic cell resource requirements in terms or direct facilities and people.

An expert system which incorporates simulation model is described in [177]. The expert system analyse the output from an FMS simulation model, determines whether operational and financial objectives are met, identifies design deficiencies, and propose designs which overcome deficiencies or exploit opportunities.

2.4.10 Summary of Other Approaches and Methodologies

Dooner & DeSilva [67] outline the development and implementation of a conceptual model in a computer system to investigate the relationship between configurations of machine and cell design and the flexibility characteristics the design exhibit. Such a mechanism should form a basis of an interactive design tool that would formally match flexibility requirements to appropriate design configurations.

Joannis & Krieger [124] utilise object-oriented approach to the specification of manufacturing systems. The specification model is built around a set of concurrent co-operating objects whose behaviour is described using communicating finite state machines. With the inclusion of the system's environment in the model, rapid prototyping of the system through realistic simulations can be performed.

An approach to the integration of advanced manufacturing systems through the combination of structured methodologies and sociotechnical design techniques is reported in O'Sullivan [195]. The technical tools used are standards, $IDEF_0$, CIM architecture and conventional modelling methods. On the social side, methods such as job design, group dynamics and appropriate project organisation are utilised.

2.5 Manufacturing System Design and Manufacturing Strategy

2.5.1 Introduction

The objective of this section is to present a discussion of manufacturing strategy through a review of the various definitions and the models that have been used in the literature. The set of competitive priorities which make up the manufacturing strategy will be elaborated in terms of the influencing factors, and in the context of advanced manufacturing systems. The close and significant relationship between manufacturing strategy and manufacturing system design decisions will be highlighted. This discussion is relevant to the development of the proposed methodology in Chapters 5 and 6.

2.5.2 Manufacturing Strategy

The ability of a manufacturing company to compete is set by its manufacturing capabilities, which must be planned with respect to the corporate objectives adopted [61, 99, 113]. This view on the strategic nature of manufacturing to the company represents a shift from the traditional perception of the role of manufacturing as only responding to marketing initiatives. The importance of manufacturing within the corporate strategy, and the structural nature of many of the manufacturing decisions have contributed to the need for the development of manufacturing strategy. In addition, the development of an appropriate manufacturing strategy is likely to have a major impact on competitiveness and company survival.

Manufacturing strategy has been viewed from many perspectives in the literature.

'Manufacturing strategy interprets business and product strategies to guide facilities planning and investment and obtain competitive unit costs." [119]

'Developed in response to corporate strategy, manufacturing strategy is a pattern of decisions over time which enables a business unit to achieve a specific set of manufacturing capabilities." [113, 220, 230]

'Based on product strategy, the manufacturing strategy defines in broad terms the manufacturing structure and infrastructure required in order to achieve the manufacturing objectives." [6]

'Manufacturing strategy is concerned with the development and implementation of plans which affect the firm's choice of production resources, the deployment of these resources, and the design of the infrastructure to control operations activities." [52, 133]

The various definitions have shown that manufacturing strategy has three generic properties of: (a) supporting the corporate objectives, (b) providing manufacturing objectives of cost, quality, dependability, and flexibility, thus offering competitive advantage, and (c) focusing on a consistent pattern of decision making within key manufacturing resources, which include structural items and the appropriate infrastructure to ensure that operations are effective.

2.5.3 Models of Manufacturing Strategy

Two inherent issues related to manufacturing strategy are those that involve decisions on the strategy process and the content of manufacturing strategy. These had been mentioned in the earlier work of Hayes and Wheelwright [110] and Skinner [241]. Models have been developed to represent these two predominant thinking and is shown in Figure 2.22 [159].

Process Model

In the *process model* the role of manufacturing strategy is shown as linking the corporate strategy and business strategy with manufacturing implementation. In this model manufacturing strategy exists in the same level as other functional strategy such as marketing and product strategies. Within each functional strategies there will be strategy formulation and implementation tasks. The manufacturing strategy process occurs within an environment consisting of markets and stakeholders. Hence, driven by the corporate objectives the manufacturing strategy will in turn determine the necessary manufacturing focus or task (i.e., what the manufacturing company must be good at) [242]. This focus can be monitored in the form of four important performance measures: cost, delivery, quality and flexibility. A clear and understandable focus will set a basis on which manufacturing resources will be managed.

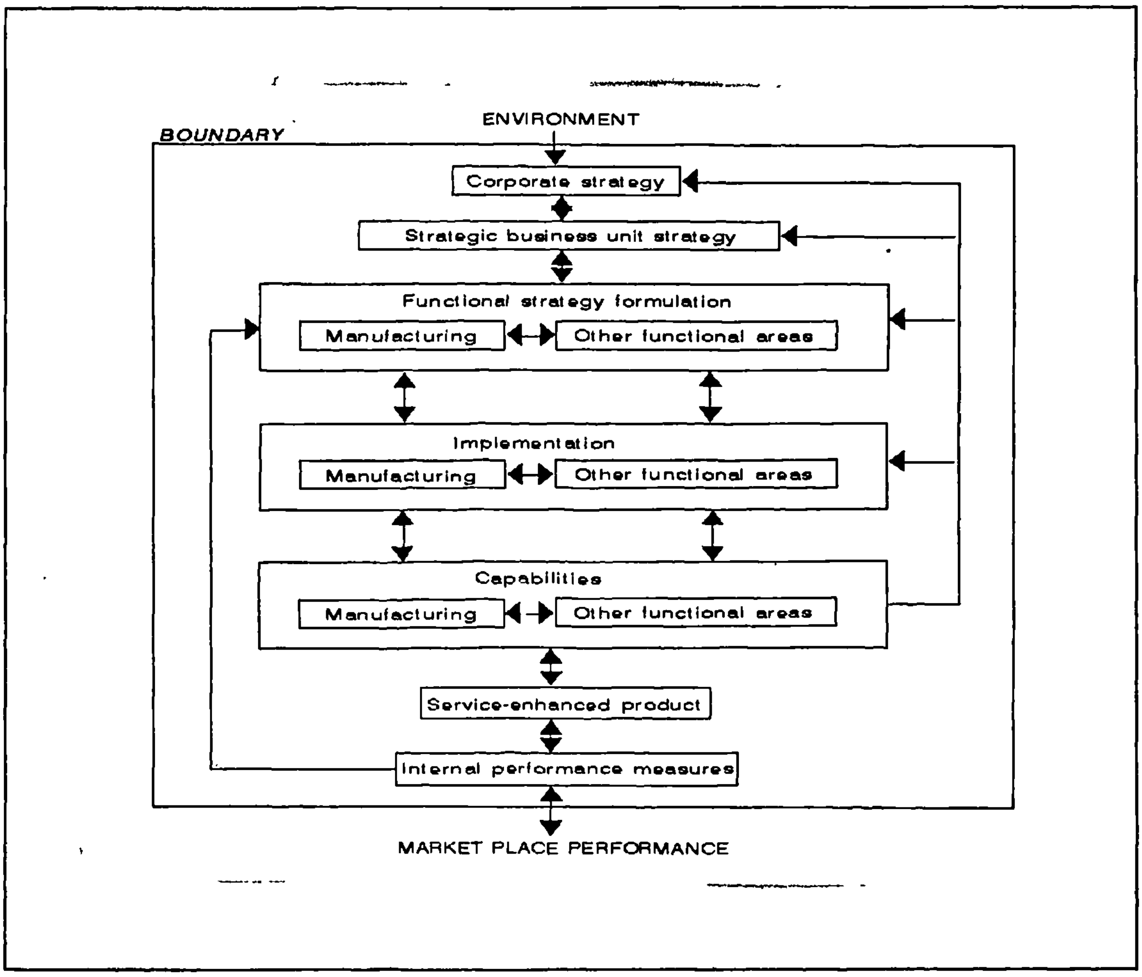
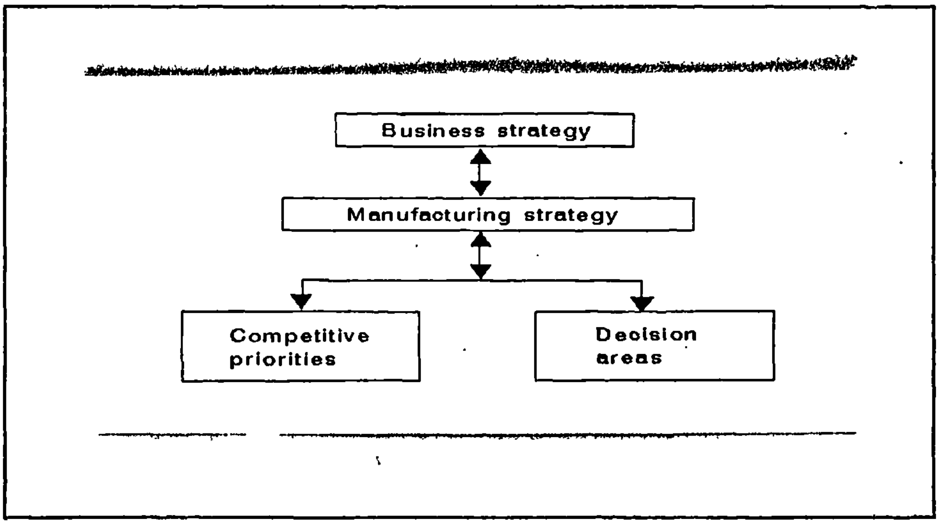


Figure 2.22 (a) Process model



(b) Content model

Figure 2.22 Models of Manufacturing Strategy [159].

	Skinner [241]	Hayes & Wheelwright [110]	Fine & Hax [82]	Linberg [164]
Structural	• Plant and equipment	• Capacity • Facilities • Technology • Vertical integration	• Capacity • Facilities • Processes and technologies	• Capacity • Facilities planning • Technology • Vertical integration
Infrastructural	• Production planning and control • Organisation and management • Labour and staffing • Product design and engineering	• Production planning and control • Quality • Organisation • Workforce • New product development • Performance measurement systems	• Product quality • Human resources • Scope of new product	• Planning and control • Work organisation

Table 2.4 Decision areas in the Content Model of manufacturing strategy

Content Model

In the *content model* of manufacturing strategy the most important elements can be captured in two broad categories: (1) decision areas that are of long term importance in the manufacturing functions; and (2) competitive priorities based on corporate and/or business unit goals. The content model which was initially developed by Skinner [241] had the competitive environment as the driver for basic business strategy which, in turn, suggests the manufacturing mission or strategy. This strategy can be encapsulated into choices made with respect to four competitive priorities: cost, quality, delivery and flexibility. Manufacturing strategy has also been characterised as consisting of a pattern of many individual decisions that affect the ability of the firm to meet long term objectives. These strategic decisions can be categorised into structural and infrastructural decisions. As shown in Table 2.4 the structural decision category addresses decisions on capital spending while infrastructural decisions affect the people and systems that make manufacturing works [82, 110, 164, 241].

2.5.4 Competitive Priorities

Competitive priorities are the elements making up a set of dimensions in the manufacturing strategy, namely price, quality, delivery, flexibility and innovativeness. These dimensions are sometimes used as measures of (external) competitiveness and sometimes of (internal) competence [55]. Thus competitive priorities may be defined as a consistent set of goals for manufacturing [16], consistent with the corporate or business unit goals. Various other terms have also been used in the literature, such as Critical Success Factors [6], Performance Criteria [2, 285], Order winning criteria [113], Value portfolio [149], Manufacturing attributes [49], Competitive criteria [72], Manufacturing strategy criteria [230], Critical manufacturing performance measures [252], Manufacturing goals [80], Competitive dimensions, [111], and Competitive-edge Criteria [191].

The next four sections will provide a brief review on the four competitive priorities that are directly related to the manufacturing activities. Although innovativeness is an important element of the competitive priority set, it is considered as not having significant role in the actual design and development of manufacturing systems. Hence detailed discussion of the topic will not be given. References on innovation in the context of design and manufacturing are available, for example [23, 31, 35, 74, 94, 213].

2.5.4.1 Price

Price is the actual money paid by the customer. It may include both initial purchase cost and expected lifetime cost. According to Hill [113], price becomes a dominant competitive advantage when there is little scope for differentiating a product. Although price is the external criterion, cost is the internal measure. Thus the objective of the manufacturing system is to produce a product which meets the given design specification and quality required as well as at a minimum cost. This low cost is necessary to support the price-sensitivity of the market-place, thus creating the level of profit margin necessary to support the business investment involved and create opportunity for the future.

Understanding the product cost structure is not only critical to comprehending the process of estimating but it is also important in cost reduction efforts. Various models of manufacturing cost have been proposed, based on the traditional structure of materials - direct labour - overheads [102, 115, 116, 190]. An example is shown in Figure 2.23 [102].

Direct Labour	+	Direct Material	=	Prime Cost
Prime Cost	+	Factory Overhead	=	Factory Cost
Factory Cost	+	Administrative O/heads	=	Manufacturing Cost
Manufacturing Cost	+	Selling Expenses	=	Total Cost
Total Cost	+	Profit	=	Selling Price

Figure 2.23 An example of traditional cost structure [102]

The Effect of Advanced Manufacturing on Manufacturing Cost

The introduction of technologies such as CNC machines, machining centres, and robots has drastically changed the manner in which real costs are calculated [185]. Specifically it has changed the distribution of indirect costs, and has reduced the contribution of direct labour cost. Automation and programmable machines have reduced the extensive need for labour. The flexible manufacturing cells and systems can be programmed to run 'unmanned' for a considerable period. The flexibility of machines and equipment also means that less specialised equipment is needed for processing. This will reduce the direct fixed costs, but on the other hand increasing the indirect fixed costs, such as change-overs and programmes. Furthermore extra maintenance is required for machines running for longer hours. Hence high investment cost of automated equipment necessitates the development of costing techniques that focus on the effective use of the manufacturing resources.

Accurate costing of products manufactured by advanced manufacturing systems such as FMS is needed for competitive bidding, pricing, make or buy decision, and other management decisions. Besides the shift in focus from that of direct labour to the optimum use of the manufacturing resources, issues such as flexibility and quality have become critical manufacturing performance measures. In dealing with these changes the conventional cost accounting methods which are based on mass production of mature product with known characteristics and a stable technology, have been found to have some limitations. These include the following: (a) Direct labour is not easily and accurately allocated to the unit being produced; (b) Direct labour does not always vary with the level of production; and (c) Overheads allocations are often inaccurate [131]. In advanced manufacturing environment, the role of overheads has become increasingly important. The overhead rates of between 500-800 percent of direct labour cost has been cited [131]. Other overheads include machine set-up costs, tooling costs, materials handling costs, equipment maintenance costs, part inspection costs, shop supervisor costs, production control costs, manufacturing engineering costs, plant facilities costs, inventory costs, fixturing costs, prototype and new-part costs, and rework and scrap costs [142]. Today it is possible to think of the machine hours and equipment costs as cost drivers and direct labour as overheads [117, 156]. The influence of quality, part waiting and equipment idleness is also significant and these are often quoted as 25-35 percent, 11 percent, and 30 percent respectively of the manufacturing cost [199].

Based on these changes, alternative models have been proposed to represent the cost structure in advanced manufacturing environment. Figure 2.24 shows a typical example of these models [199]. The model indicates the reduction in the impact of direct labour cost, by combining it with indirect labour and aggregated to labour cost. The prominence of overhead is shown by its components of set-up labour, machine, tool and floor space. The software cost reflect the significance of manufacturing computerisation.

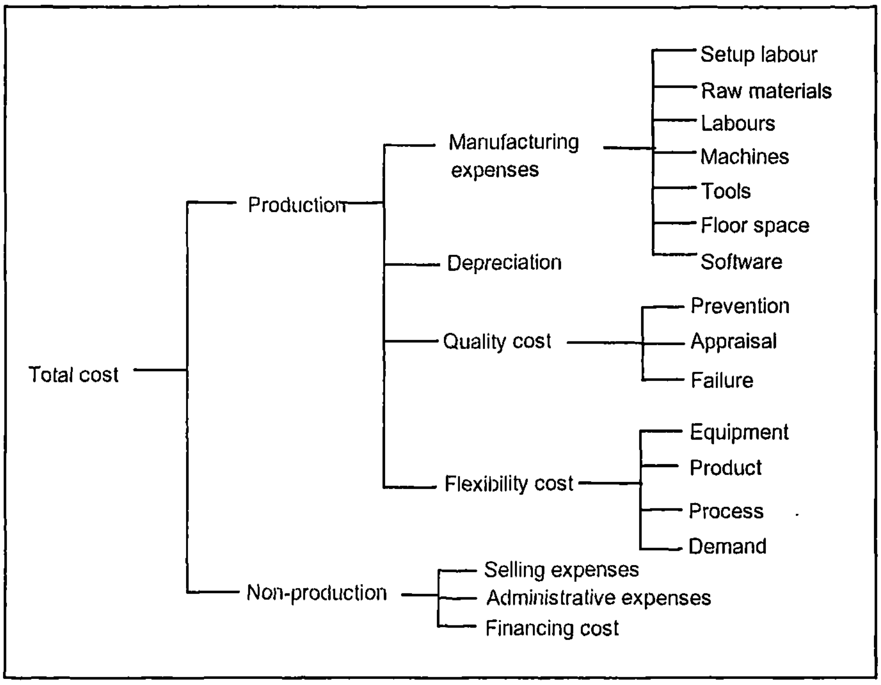


Figure 2.24 An example of cost structure for advanced manufacturing system [199]

2.5.4.2 Quality

Quality is one of the important market dimensions of the manufacturing strategy. There are various definitions of product quality, some of which include: 'its ability to satisfy stated or implied needs' [33]; 'conformance to customer's requirements' [56, 79]; and 'fitness for purpose or use [125]. These definitions indicate that quality of a product is fundamentally related to meeting the customer satisfaction. However it is difficult to define quality in quantitative terms as customer satisfaction depends not only on the actual features of a product, but also on a host of other subjective factors. Garvin [90] identifies eight dimensions of quality on which companies should compete, see Table 2.5.

Dimensions of Quality	Description	Function typically responsible for their provision
1. Performance	A product's primary operating characteristics	Design
2. Features	Secondary characteristics	Design
3. Reliability	The probability of a product malfunctioning within a given period	Design
4. Conformance	The degree to which a product is manufactured to the agreed specification	Manufacturing
5. Durability	A measure of a product's life in terms of both its technical and economic dimensions	Design
6. Serviceability	The ease of servicing to include the speed and provision of aftersale service	Design and aftersales
7. Aesthetics	How the final product looks	Design
8. Perceived quality	How a customer views the product	Design

Table 2.5 The dimensions of quality [90]

The quality of products is influenced by the activities within manufacturing system such as product planning, product design, process design, production and after sale service. With regard to advanced manufacturing systems, quality has two important considerations:

1. The move from a mass-production system, where repeatability of the manufacturing process becomes important, towards low volume or even one-of-a-kind production, has rendered necessary adjustments to the statistical methods

since the population of items that are typically used for deriving statistically meaningful measures for quality may not be available [49].

2. It has also been observed that many companies are moving from manufacturing process quality control to product development quality control. This is undertaken to overcome the limitation of statistical quality control as defect prevention through variation reduction [85].

Once the product specifications have been established and appropriate processes are decided, the task of the manufacturing system is to ensure that the products adhere to the specified standards. This is achieved through two approaches: quality control and quality assurance. *Quality Control* is concerned with those activities related to inspection of product and component quality, detection of poor quality, and corrective action required to eliminate the poor quality. These activities also involve the planning of inspection procedures and specific gauges and measuring instruments needed to perform the inspection. The instruments normally used are the control charts. *Quality Assurance* is concerned with those activities which will maximise the probability that the product and its component will be manufactured within the design specifications. Quality assurance activities involve all the departments that are involved in the manufacturing of products.

2.5.4.3 Delivery

Delivery is an important requirement put on the manufacturing organisation by the customers. Both aspects of delivery i.e., delivery reliability and delivery speed are important attributes of time. *Delivery reliability* is a measure of how a manufacturing system can deliver on time, and *delivery speed* is the ability to deliver more quickly than its competitors. Hill [113] provide detail discussion on delivery reliability and delivery speed and consider them as important order winning criteria. Ashton and Cook [10] on the other hand consider delivery reliability as a fundamental requirement for a manufacturing firm to compete upon. Thus meeting delivery requirement is an important aspect of time-to-market (TTM) concept [207].

The way time is managed has also been mentioned as a powerful new source of competitive advantage for leading companies [253, 270, 274]. As a strategic weapon, time is the equivalent of money, productivity, quality, and even innovation. The work of Schmenner [231] has shown that the management focus on throughput time has knock-on effects on the reduction of inventory, set-up time and lot sizes, encourages improved quality, factory layout, stabilised production schedules and minimised engineering changes.

Despite the significant influence delivery has on the competitiveness of manufacturing firms, it has been mentioned that of all resources used in manufacturing operations, the most critical and least well managed is time [210]. In fact few companies treat the management of time as a strategic issue at all [47].

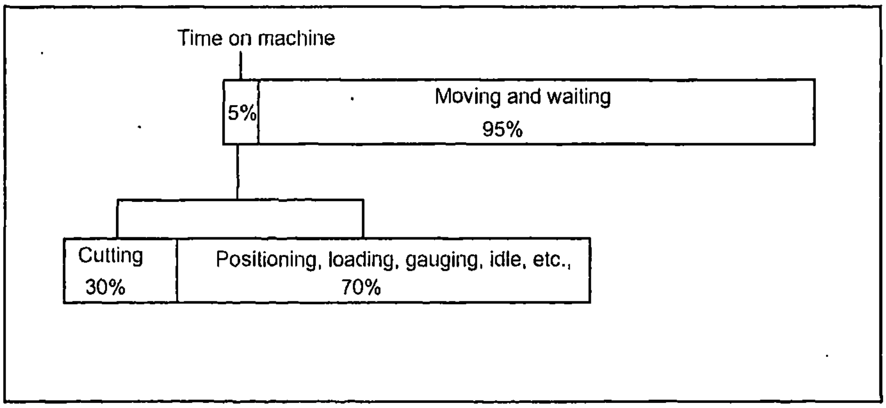


Figure 2.25 The elements of throughput time (process lead time) [38]

Throughput time is the most important time element as it truly reflects the capability of a manufacturing system. Figure 2.25 shows the elements that constitute process lead time [38]. Of an average of 5% of the time that a part spends on a machine, less than 30% is spent in the actual metal removal. Production rate is the term sometimes used to indicate how quickly a product can be produced by the system [49]. The production rate of a system is the number of acceptable pieces produced per unit time, taking into account delays during production and unpredicted interruptions such as machine breakdowns. Thus the production rate of a manufacturing system is significantly affected by the reliability of the equipment and the overall structure of the system. As will be discussed later, higher production rate would also result in lower cost and possibly lower quality as well.

Lead time reduction is an important manufacturing system design consideration which can be achieved more effectively by managing the resources employed. These include preventing bottlenecks in all processes, controlling the job queues at each work centre, and eliminating the lead times for non-added value activities [20]. Groover [97] presents a number of automation strategies that can be adopted in order to reduce lead time, by considering that manufacturing lead time (MLT) can be represented as

$$MLT = N_m(T_{su} + QT_o + T_{no}),$$

where $T_o = T_m + T_h + T_{th}$; N_m = number of machines; T_{su} = set-up time; Q = batch quantity; T_o = operation time per machine; T_{no} = non-operation time for each process; T_m = actual processing time; T_h = workpiece handling time; and T_{th} = tool handling time per work piece.

Strategy	Manufacturing function	Objective to reduce
Specialisation of operations	1	T_m, T_o
Combined operations	1.2	T_h, T_{th}, N_m
Simultaneous operations	1.2	T_h, T_m, T_{th}, N_m
Integration of operations	1.2	T_h, N_m
Reduce set up time	1.3	T_{su}
Improve materials handling	2	T_{no}
Process control and optimisation	1.3	T_m
Computerised database	4	N_m, T_{no}
Computerised control	3.4	T_{no}

Key to the manufacturing functions: 1=Materials processing and assembly; 2=Materials handling; 3=Control - process and plant level; and 4=Manufacturing database development.

The benefits typically gained from reducing the lead time include: meeting the delivery requirement, flexibility to adapt more quickly to changes in demand, reduced WIP inventory, and easy accommodation of design changes. Besides contributing to the reduction in the lead time, the reduction of set-up time also significant in determining the success of just-in-time (JIT) implementation [249].

2.5.4.4 Flexibility

Flexibility in manufacturing means being able to reconfigure the manufacturing system so as to produce efficiently in the changing environment [66, 67, 101, 235]. Manufacturing flexibility is one of the key issues in the design, operations and management of manufacturing systems today. Three factors that govern its prominence are (1) the increasing turbulence of the market in which manufacturing companies operate, as reflected by the great variation in demand for products and services, the competitive markets, shorter product life-cycle, quicker development of new products, increasing variety of product, etc.; (2) the availability of new manufacturing technologies based on microprocessor technology which has widened the scope of system selection; and (3) the change in the nature of production management aims which has widened beyond the scope of cost and productivity issues alone. Many types of flexibility have been described and these are summarised in Table 2.6 [14, 36, 136, 150, 235]

Manufacturing flexibility clearly has major implications for a firm's competitive strength, and makes it an important part of the firm's strategy. Increasingly flexibility is considered as a critical success factor, in addition to the traditional factors of cost and quality. De Meyer et al. [63] for example, argue that flexibility is the next competitive battle in manufacturing. However it is interesting to note that in an earlier paper, Jaikumar [121] observes that the US manufacturing companies which installed the FMS systems (considered to be important instruments of flexibility) did so merely to reduce their manufacturing costs, rather than to utilise the flexibility provided by such systems as a new competitive weapon.

Flexibility is a very complex concept. At the production organisation level, flexibility is a function of four interrelated variables [164]: (1) Flow structure and layout, (2) Equipment and machinery, (3) Control and system, and (4) Work organisation. Flexibility can be achieved through manipulating any of the four factors - each is dependent on the conditions set by the other three. Any one of them can also limit the flexibility of a system. Kim [136] provides the following factors that can influence the operational flexibility of the manufacturing systems: factory network; supplier network and relations; workforce; rules and procedures; machine and equipment; and information systems.

Flexibility type	Definition	Measurement	Attainability
Machine	The ease of making the changes required to produce a set of part type	• the time to replace worn-out or broken tools • time to change tools in tool magazine • time to assemble or mount new fixture	♦ technological progress - tool and part loading ♦ proper operation assignment ♦ capability of bringing part and cutting tools to the machine together
Process (mix)	Mix of jobs that can be processed in the system, or the ability to produce a given set of part types in several ways	• number of part types that can simultaneously be processed without using batches	♦ machine flexibility ♦ multipurpose CNC machining centre
Product	Ability to changeover to produce a (new set) of product(s) very economically and quickly	• time required to switch from one part mix to another	♦ machine flexibility ♦ an efficient and automated production planning and control system
Routing	Ability to continue producing a given set of part types by alternate routes, when necessary (e.g. breakdowns)	• by the robustness of the system when breakdown occurs, and not decreasing the production rate	♦ Automated rerouting of parts by pooling machines into machine groups
Volume	Ability to operate manufacturing system for different production volumes profitably	• variation in batch sizes for all part types with the system still run profitably	♦ multi-purpose machines ♦ a layout that is not dedicated to a particular process ♦ automated, intelligent material handling system ♦ routing flexibility
Expansion	The capability of building a system, and expanding it as needed, easily and modularly. The ease with which the capacity and capability of a manufacturing system can be increased when needed.	• according to how large the system can become	♦ having a non-dedicated, non-process driven layout ♦ having s flexible materials handling system ♦ modular, FMC with pallet changes ♦ routing flexibility
Operation	The ability to interchange the ordering of several operations for each part type	• The number of different processing plans for part fabrication.	♦ through product design
Production	The universe of part types that the system can produce	• the level of existing technology	♦ increasing the level of technology and the universality of the machine tools ♦
Material handling	Ability of a MHS to move different part types efficiently for proper positioning and processing	• The number of different paths that the system can support	♦ A combination of type and layout design of transporting devices
Market	The ease with which the manufacturing system can adopt to a changing market environment	• Weighted measures of effort in terms of time and cost required to introduce new products or to change production volume	♦ Close integration of production planning and inventory control with marketing functions

Table 2.6 Types of flexibility.

The introduction of new manufacturing technologies such as Automated Guided Vehicle (AGV), Automated Material Handling (AMH), Computer Aided Design (CAD), Flexible Manufacturing System (FMS) and Computer Integrated Manufacturing (CIM) has generally increased the attainment of flexibility. However there are limitations. The machine tools themselves are so flexible, that they can be used in any production system, but the way they are controlled or integrated in an FMS is specific for the particular system. The control system architecture is a function of part types, process times, physical layout of the machines etc. Optimisation of the control logic is specific to a particular system. A study on factors that affect the flexibility of the various types of production systems identifies the variables that influence flexibility as the number of parts and products, the length of total lead time, quantity of inventory and level of amplification of production and of inventory quantity in each stage of the system under the condition of investment and production cost (for multistage production) [186].

2.5.5 Measures of the Competitive Priorities

For a given competitive priority, a measurement of the performance criteria are necessary in order to assess the impact of manufacturing strategy on the organisation. Some indication on the measurement criteria associated with respective priority is given in Table 2.7 [2, 72, 159, 294]. Son and Park [251] consider productivity, quality and flexibility to be the critical manufacturing performance measures. These measures are quantified and combined into one global index called Integrated Manufacturing Performance Measure. This index is used as a primary evaluation of a manufacturing system as a whole. Babbar and Rai [14] proposed surrogate measures for some of the more important dimensions of manufacturing flexibility. A measure of machine flexibility can be obtained by computing the ratio of set-up time to processing time. Low ratios identify higher levels of process and product flexibilities. The throughput relative to machine downtime provides a reasonable measure of routing and operation flexibilities.

Dimension	Examples of measurement criteria
Cost	Unit product cost Unit labour cost Unit material cost Total manufacturing overhead cost Inventory turnover Capital productivity Capacity/machine utilisation Materials yield Direct labour productivity
Quality	Internal failure cost - scrap rework, percentage defective/rejected External failure cost - frequency of failure in the field Mean time between failure Number of engineering changes Incoming supplier quality
Delivery performance (I) Dependability (ii) Speed of delivery	 Percentage of on-time deliveries Accuracy of inventory status Average delay Master production schedule performance stability Delivery lead time
Flexibility (I) Volume (ii) Product mix	 Average volume fluctuations that occur over a given time period divided by the capacity limit Number of components handled by the equipment Ratio of number of components processed by the equipment to total number processed by the factory
Innovativeness	Level of R&D investment Consistency of investment

Table 2.7 Measurement criteria for competitive priorities [2, 72, 159, 294].

2.5.6 Competitive Priorities Trade-offs

Trade-off among the competitive advantages need to be considered as it is impossible for a firm to excel in all of them simultaneously. Good manufacturing practice means focusing on a limited subset of competencies or competitive priorities [242]. Thus given a particular environment, a manufacturing strategy should ensure that the right competitive dimensions are developed and followed. Optimal utilisation of organisational resources also requires that manufacturing companies place the necessary degree of relative importance to the competitive advantages. Table 2.8 provides a summary of the typical priorities found in the literature which indicates that generally the order of relative importance of the competitive priorities is: quality, delivery, cost and flexibility.

Early conceptual work on competitive priorities stressed trade-offs between cost and quality, or between dependability and flexibility [16, 82, 219, 241]. However it has been shown by the Japanese manufacturers that such trade-off is unnecessary, and the real issue is identifying techniques to improve quality that will affect reduction of the overall cost [286], and also of combining low cost manufacture with flexibility [81]. New [191] argues that despite the world class manufacturing, the issue of trade-offs is still very much relevant. In a study of seven trade-off situations, quality capability and true design flexibility are still highly relevant to the choices which companies make in relation to the most appropriate manufacturing mix (plant, process, people, and product) for their competitive criteria.

Author	Order of Competitive Advantages (1=most important; 4=least important)			
	cost	quality	delivery	flexibility
Schroeder, 1986 [233]	3	1	2	4
Ang, 1989 [6]	1	3	-	2
De Meyer, 1989 [63]	3	1	2	4
Somers & Gupta, 1992 [251]	3	1	2	4

Table 2.8 Typical priority attached to competitive advantages.

The conclusion that can be drawn from this discussion is that there is a need to prioritise the competitive advantages in order to achieve resource optimisation during the design and planning of manufacturing systems. Further, such step will provide focus for the manufacturing firms to achieve the specific business objectives. Despite the widespread discussion in the literature on the importance of manufacturing flexibility, there appears to be no evidence that this competitive priority being addressed explicitly in the design of manufacturing systems.

2.5.7 Manufacturing Strategy and Manufacturing System Design Decisions

Discussions in the previous sections have shown that business objectives are related by manufacturing strategy to production where objectives are transformed into decisions on the implementation or integration of modern technologies. Investment in technology by itself does little to improve competitiveness and profitability [276]. There is a growing awareness in industry that the key to competitive manufacturing lies in developing a manufacturing strategy that satisfies the business needs. Technologies such as CIM are nothing more than a tool which of itself can do nothing to increase competitiveness except when it fits with the required manufacturing strategy [134].

The provision of a 'strategic link' between business objectives and technology in the context of manufacturing is important as this will ensure strategic consideration of technology in the context of market characteristics, competitive response, economic trends and other environmental variables. Kantrow [128] for example, considers technology as having an integral relation to a company's strategic thinking by helping to define the range of its possibilities. Kruse [148] argues that only if manufacturing becomes an accepted and active part of the whole strategic business planning cycle will a company be able to develop manufacturing systems which help to optimise overall competitive business performance. The definition of the elements of business strategy which consists of manufacturing strategy, product engineering strategy, manufacturing systems engineering strategy and financial information and control strategy has been considered as the starting point for the design and control of manufacturing systems [205]. The manufacturing strategy is such that the particular process technologies and their capabilities required to make quality products must be determined, machinery specified and matching interfaces with customers and suppliers determined.

Various approaches and models have been proposed to show the relationship between manufacturing strategy and manufacturing system design decisions [84, 112, 148, 248, 280, 285, 291, 294]. Figure 2.26 shows the model proposed by Williamson [291]. In this model, a two-phase, six-stage process leading to the implementation of integrated manufacturing systems is presented. The first phase is concerned with developing manufacturing strategy which represents an outline of the plan. The second phase refines the manufacturing strategy into more detailed plans leading to the implementation of appropriate systems.

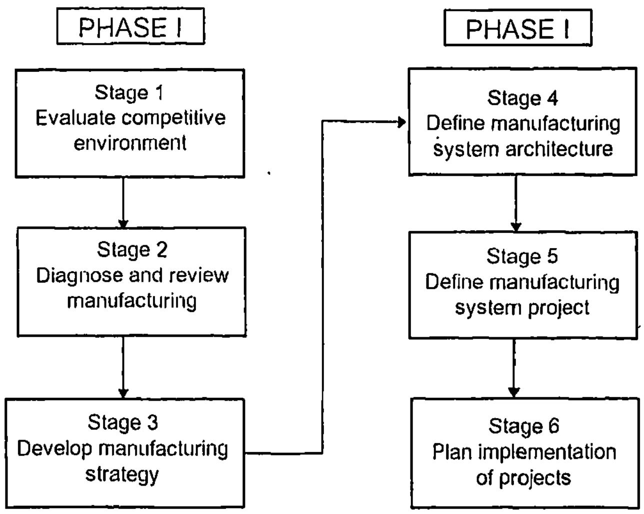


Figure 2.26 Manufacturing strategy and manufacturing system design decisions [291]

Naik & Chakravaty [189] proposed a framework that incorporates the intangible and complex strategic benefits with operational and financial evaluations of manufacturing technology evaluation. The framework ensures that the selection of the type of new technology is consistent with the competitive strategy.

An approach which relates business objectives to the choices of technologies based on the probabilistic linear regression of fuzzy data sets with the aim or working towards computer integrated manufacturing is proposed by Foong and Hoang [84]. The business objectives are expressed in terms of critical success factors or manufacturing strategies such as lower rejects, lower batch size, improved set-up, shorter lead time, lower WIP and increased flexibility. The technologies involved include GT, JIT, Kanban, Kaizen, MRPII, CAD, CAM, Robotics, AMH, ASRS and CAE. It is claimed that the approach gives a better conclusion for management, as the model takes into consideration the fuzziness of the relationships between CIM technologies and business strategies.

A model for developing a production strategy by the simultaneous manipulation of design variables within the four functional areas of the manufacturing system has also been suggested [99]. The functional areas are production technology, plant layout, production planning and control and organisation and management system. The production technology focuses on individual machines and machining centres. The plant layout deals with the physical structure and arrangement of such machines. The planning and control system concentrates on material flow, and the organisation and other management systems focus on the individuals and their interplay. A production strategy exists when mutually co-ordinated strategies have been deployed for each area.

Yang and Deane [296] address the relationship between several specific cell formation design decisions and major performance criteria. They argue that cell formation design decisions must be viewed as multi-criteria decision-making problems, including strategic considerations which are expressed in terms of the competitive priorities. Ultimately, cell formation design decisions will have to satisfy the dynamic and changing customer requirements.

2.6 Summary

The chapter has presented a literature review on manufacturing systems, the nature and problems of manufacturing system design, the design methodologies and tools used, and the relationships that exist between manufacturing strategy and manufacturing system design decisions. Flexible manufacturing (either in the form of cell or system) is an approach that is suitable for mid-volume, mid-variety products. Such systems need to be properly designed to ensure successful operations and hence realising the potential benefits. The design process involves matching the performance requirements onto suitable decision variables. The design of manufacturing systems can be divided into two aspects, i.e., structural design and operations design (also called production planning). Structural design problems include part-machine grouping, system design, equipment selection and facilities layout. Each design problem can be resolved by a number of methodologies and tools. These range from systems engineering approach and structured methodology to operational research and artificial intelligence. The objective of design is ultimately to fulfil the requirements of the market, which can be encapsulated in four competitive advantages of the manufacturing strategy, i.e., price, quality, delivery and flexibility. It is argued that manufacturing system design cannot be divorced from these strategic issues. In fact evidences in the form of conceptual models have been collated that prove such claim.

The literature review has also indicated that there is a lack of published work that deals with how the link between manufacturing strategy and manufacturing system design decisions can be exploited further. This is with regard to actually translating the competitive priorities into the design construct of manufacturing systems. Hence there is a need for a design methodology that is based on this strategic connection.

CHAPTER 3

QUALITY FUNCTION DEPLOYMENT

3.1 Introduction

This chapter will describe Quality Function Deployment as a methodology that has been originally developed for product design and development. The discussion will centre around the conceptual framework of the methodology, the processes involved, the benefits (either potential or those that has been reported), the three main approaches that have been developed, as well as the development and potential use of the methodology in other applications.

3.2 Definition

Quality Function Deployment (QFD) is a method for translating customer requirements into appropriate company requirements at each stage, from research and product development, to engineering and manufacturing, to marketing/sales and distribution. In other words, QFD can be considered as the process of taking the *voice of customers* (or users) all the way through product (service or systems) development to the factory floor and out into the market place [4]. It is regarded as a comprehensive method for matching customer requirements to engineering characteristics of a product.

QFD is not just a quality tool, but it is an important planning tool for introducing new and upgrading existing products, processes, and services. It focuses on understanding the customer's requirements and making sure they are addressed in the product at the design stage, where about 60-80 % of the total cost of a product is committed. The premise of the QFD method is that it recognises the significance and importance of the person who buys (or who most influences the buying decision) a product in determining the commercial success of a product. Thus the voice of the customer should be given the highest priority in determining the product's attributes. One of the strengths of QFD is to give the product design/development team the opportunity to look at different options before deciding on one particular design. QFD focuses and co-ordinates skills within an organisation, first to design, then to manufacture and market goods that customers want to purchase and will continue to purchase. These are implemented through the extensive use of analysis and documentation in the form of charts.

The use of QFD is appropriate when some of these symptoms are shown by manufacturing companies: increasing complaints from customer on products/services, market share has been consistently declining, extended product development time due to excessive redesign or problem solving, lack of true customer focus in product development process, poor communication between departments or functions, lack of structure of logic to the allocation of resources, and lack of efficient and/effective teamwork.

The concept of QFD was first proposed by Dr Yoji Akao in 1966. The idea was born out of the need to find a way to get the production units to grasp the notions of quality assurance at the stage of planning even before going into production of new goods [4]. The QFD technique was further enhanced by the development of a matrix of customer demand and quality characteristics at Kobe Shipyard of Mitsubishi Heavy Industries. It has been used to get engineers to consider quality early in the design process. The technique was popularised in the United States in the early 80's and was later introduced in Europe in the early 90's.

3.3 Conceptual Framework

The concepts that constitute the QFD paradigm can be summarised along the following central issues [64, 85, 108, 258]:

1. *Moving Upstream Philosophy* The traditional, 'post-process', way to control quality is to inspect the products before they are packed and shipped. This later developed into the more conventional method of detecting variations on the product or process and put resources in reducing the variability. Thus the use of Statistical Process Control has become widespread in the industry. However the use of Statistical Process Control is at best an effort to reduce variations which, due to design are inherent in the product after a product has been released for production.

Quality Function Deployment is a methodology that has been developed to help manufacturers make the transition to business operations that are preventive rather than reactive. QFD is a method which operates by shifting the traditional manufacturing quality control upstream to product design quality control [85]. Manufacturing quality control deals with physical products which may be touched and measured. In product design quality control many intangible items are dealt with often before the design has even matured into 'lines on paper". This represents the philosophy of most of the Japanese companies which put more effort into designing quality at the product development stage.

2. *A customer satisfaction mindset* QFD is a systematic approach to planning and decision-making in product design and development that is driven by the customer needs. The set of customer's requirements expressed in their own terms is called the Voice of the Customer. Under the QFD approach, every project starts by understanding the requirements of the customer and prioritising them. As the project progresses the consideration of design, processing, assembly and other practical issues are discussed relative to what customer needs. Requirements that are new, difficult and important are highlighted as critical to keep the project focused.

3. *People and teamwork* Although QFD techniques can be used by individuals, its true potential can be realised through the existence of an interdisciplinary team. The team should be cross-functional and have representatives from each organisational unit that must link together to produce the product or service. Superior products are the result of people working together with a sense of shared vision and responsibility.

4. Connectedness A structured approach to developing internal specifications and technical requirements is necessary to ensure that the product development process is efficient. When fully utilised, QFD provides a systematic way for the external customer's voice to flow through the product development process connecting these technical requirements for each stage of product development and production and focusing them on the customer's wants. Counterpart Characteristics is the term used to describe the critical final product control characteristics. It expresses the voice of the customer in technical language that specifies customer-required quality. Product Quality Deployment is a set of activities needed to translate the voice of the customer into counterpart characteristics. Deployment of the Quality Function - activities needed to assure that customer-required quality is achieved; the assignment of specific quality responsibilities to specific departments.

5. The use of matrices QFD is associated with the use of matrices to translate the voice of the customer into final product control characteristics. Matrices are useful in arranging facts and data as a means of communication. Each matrix functions to achieve particular objective.

3.4 The QFD Process

The QFD process can be explained in terms of a three-phase process - quality design, detailed design, and process deployment, as shown in Figure 3.1. Each stage of the deployment, or translation is accomplished by the use of a QFD matrix as a tool, which essentially captures a number of issues pertinent and vital to the planning process. The QFD matrix has two principal parts. The horizontal portion of the matrix contains information regarding the customer. The vertical portion of the matrix contains a technical translation of this customer information.

The QFD process starts with the customers and their wants and needs, often referred to as 'The Voice of the Customer'. Product attributes such as 'feel/look good', 'easy to use', 'works well', etc. are normally stated qualitatively and are vague, albeit, they are important to the customer. There are many ways to gather this 'voice', ranging from surveys and interviews through market studies, product complaints and product screenings. Although many customers may exist throughout the development of any item, the end user should always be of utmost importance.

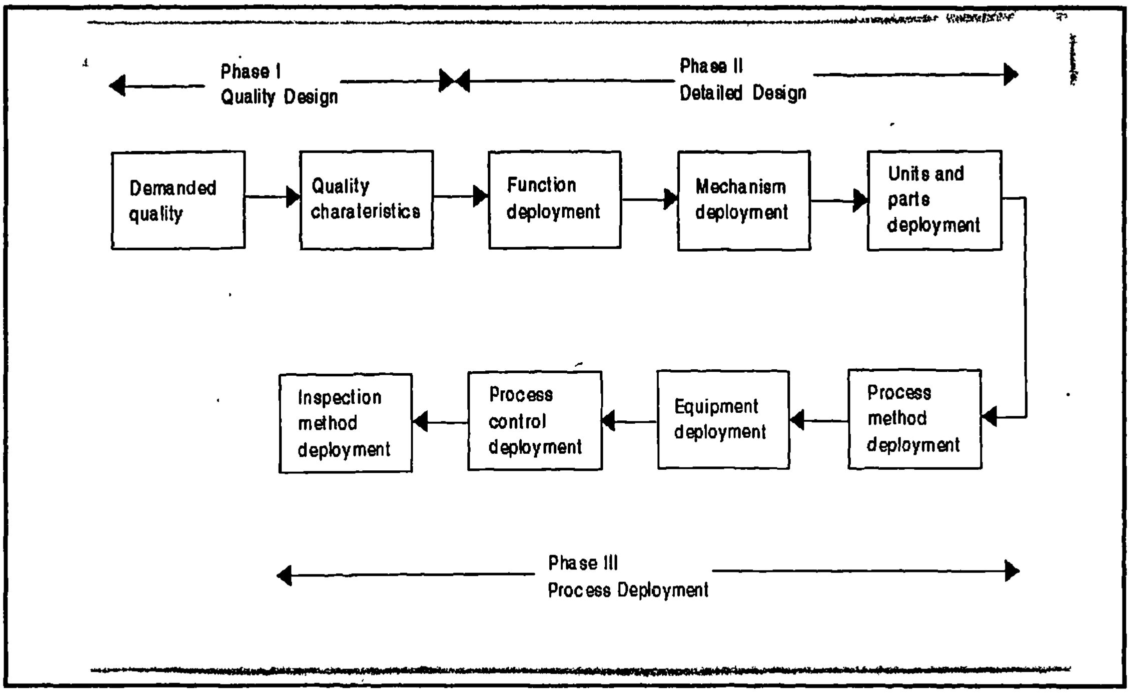


Figure 3.1 The QFD process [4].

Once gathered this voice is grouped logically and then translated into outputs (measurable design requirements) related to achieving the customer's wants. These are internal company requirements, which are generally global product characteristics such that if properly executed the product will satisfy the customer requirements. Products are not normally implemented at this global level, but rather implemented at the system, sub-system and part level. The global design requirements must then be translated into specific parts and critical characteristics of these parts which cause the essential functions to be performed. This translation (as in each succeeding translation) is accomplished by the application of engineering and technical knowledge to establish the requirements of what is to be provided by the item being developed. Relationships between the various wants (inputs) and requirements (outputs) are established through the use of the planning matrix to provide focus on key aspects of the item being developed. After establishing the requirements (including target values) and key relationships, the next translation (or deployment) can be made using this information as inputs.

In the process deployment phase, the determination of the required manufacturing operations is often constrained by previous capital investment. Within this operating constraints manufacturing operations which are most critical to creating the desired critical part characteristics, as well as the process parameters of those operations which are most influential are resolved. The manufacturing operations are then evolved into production requirements, which are the entire set of procedures and practices which will lead the production system to build products which will ultimately satisfy customer requirements. These operating procedures determine the method by which the factory will operate the manufacturing process to consistently produce the required critical part characteristics. They will include a number of 'soft' issues such as inspection and Statistical Process Control (SPC) plans, preventive maintenance programs, operator instruction and training.

3.5 The House of Quality

The House of Quality is the basic design tool used for QFD projects [4, 108]. There is a misconception that assumes that the House of Quality and QFD are one and the same. The fact is that, the House of Quality (HOQ) (also called product planning matrix) is just one of the tools employed in implementing the QFD methodology. Other tools used include affinity diagrams, relations diagrams, hierarchy trees, process decision program diagram, the analytic hierarchy process, and blueprinting. The house of quality is a kind of conceptual map that provides the medium for interfunctional planning and communication. It is the most widely used tool in QFD. People with different problems and responsibilities can thrash out design priorities and reach consensus on the actions that they should take, while referring to patterns of evidence on the house's grids. There are seven logical steps in completing the House of Quality (Figure 3.2).

Step 1 - Determine customer's requirements

The customer requirements are identified and defined qualitatively. This step involves completing the room of the HOQ called the WHATs room or The Voice of Customer. The Voice of Customer is a technical term within QFD. It has a specific meaning. It is a short verb-object combination containing one thought that represents what is it that the customer wants, needs, or would be delighted with. It is the attribute that the product or service must have to make the customer happy. It may not be a set of characteristics that the company thinks the customer wants.

Step 2 - Prioritise the list

The purpose of this step is to establish the priorities for action. This step includes completing the rooms called Customer Importance (or Weighting) and Market Evaluation. Customer Weighting is to establish the strength of feeling that the customer has for each voice. It is a relative indication of the significance of each voice in the customer's overall long term satisfaction. The Market Evaluation is to establish the priorities based on competitive benchmarks, the corporate history of complaints, the product sales strategy, etc.

Step 3 - Establish the Design Requirements

In order to translate customer requirements into global product characteristics (or Design Requirements) the list of WHATs is refined into the next level of detail by listing one or more HOWs for each WHAT. These are more objective (measurable), and actionable technical requirements. Further properties of the HOWs include: having no design constraints (global), must represent a response to customer's voice, must be proactive, and must be practical.

Step 4. Determine the relationships between the WHATs and the HOWs

The relationships between the WHATs and HOWs could be complex as some of the HOWs could affect more than one WHATs and can even adversely affect one another. To overcome the problems arising due to these complex relationships, the relationships are defined in a matrix format, by completing the room called Relationship Matrix. The matrix provides an opportunity to examine each customer's voice against each technical requirement and to evaluate the strength of the relationships. The strength of the relationship is categorised as Strong, Medium, or Weak. These measures of the relationship are based on engineering judgement, experience, statistical studies and experimentation. Decisions will then be made whether the organisation would work on this technical requirement to respond to the customer's wants and needs, and if the organisation works on this technical requirements and meets the targets set for it, how strongly will that affect the customer's satisfaction relative to the voice. Due consideration is also given to company goals and objectives for stronger competitive positioning.

Step 5 - Establish Technical Targets HOW MUCH is the measurement for the HOW. The HOW MUCHes provide specific objectives which guide the subsequent design and afford a means of objectively assessing progress. The purpose of this step is to establish technical targets for each Design Requirements representing the numeric level that would provide the highest customer satisfaction if achieved.

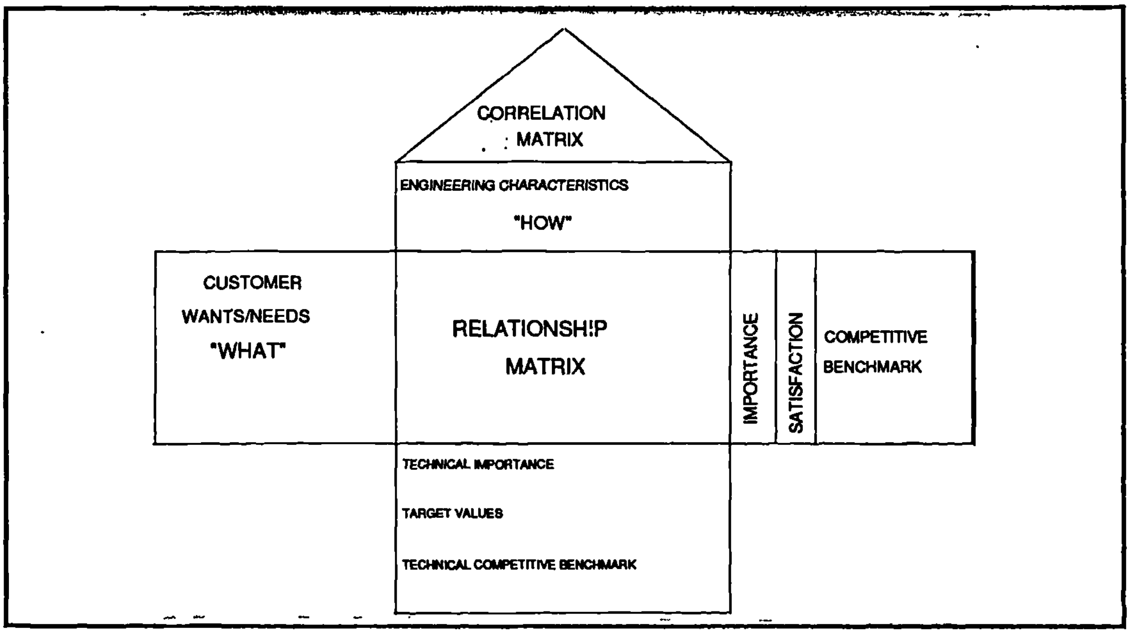


Figure 3.2 The House of Quality.

Step 6 - Establish the Correlation Matrix Correlation Matrix is a triangular table attached at the top of HOWs, forming the 'roof', and establishing the correlation between each HOW item. The relationships among the HOWs will indicate areas where trade-off decisions and further research and envelopment which may be required. The correlations are categorised as Positive, Strong Positive, Negative and Strong Negative. Positive correlation indicates that one HOW supports another HOW, and this is where resource efficiency can be attained. Negative correlation indicates conflict between one HOW and another. It represents a condition in which trade-off's are required.

Step 7 - Take Action The purpose of this step is to identify which issues are most critical to improving the customer's overall satisfaction with the product based on the data arranged in the chart. Critical items are those that are either new, difficult or important. They are usually items that need to be solved or improved by inter-functional teamwork within the organisation. If customer importance rating (priority) is represented by an (mx1) column vector X, and the strength of relationship as an (mxn) matrix Y, then the technical importance ratings become a (1xn) row vector, Z, computed as follows:

$$Z = X^T Y$$

Each Z_j is the technical importance rating for HOW j from j = 1, 2, ...n , and gives an indication of how important each HOW is in accomplishing the customer requirements. Executed correctly, analysis of this matrix provides a project team with a product specification that is customer focused and which identifies the characteristics that are the most important and fundamental to customer satisfaction.

3.5.1 The Houses Beyond

The House of Quality, or sometimes called Product Planning Matrix (A-1 Matrix), is the foundation matrix on which further stages of the methodology are developed. It deploys customer requirements into product characteristics. After the House of Quality, a QFD study may proceed in any number of directions. If quality and functionality are critical, the study would ordinarily proceed to the design and then the process stages. In studies where the effects are related strongly to manufacturing issues, they may proceed directly to the process stage. In the normal process, the 'HOWs" from the House of Quality become the 'WHATs" of another house. The process of setting up the quality table where the number could range from four [108] to thirty [138].

3.6 QFD Approaches

There are three main approaches to QFD which have evolved from the basic process. They are the American Supplier Institute (ASI) Approach, the GOAL/QPC Matrix of Matrices Approach, and the International TechneGroup Incorporated (ITI) Approach. The three approaches represent variations of the development that have taken place in quality function deployment concept. Each is based on the same principle of meeting customer needs, and uses very similar techniques. The selection of suitable approach depends on the scope of the project to be implemented. Despite the availability of these approaches, the applications of QFD are very much subject to customisation and integration with other aspects of management.

3.6.1 The American Supplier Institute Approach

The American Supplier Institute (ASI) approach is based principally on the use of the house of quality. It is a four phase approach as proposed by Akao [4]. Each phase provides the next level of information required which is then prioritised to show the key requirements. This provides a continuous focusing towards the criteria necessary to achieve customer satisfaction. Information from one phase of QFD flows through into the next. As shown in Figure 3.3 the phases provide the following:

- Phase 1 - translates the customer wants into design requirements.
- Phase 2 - translates design requirements into critical part characteristics.
- Phase 3 - translates critical part characteristics into critical process parameters.
- Phase 4 - translates critical process parameters into production requirements.

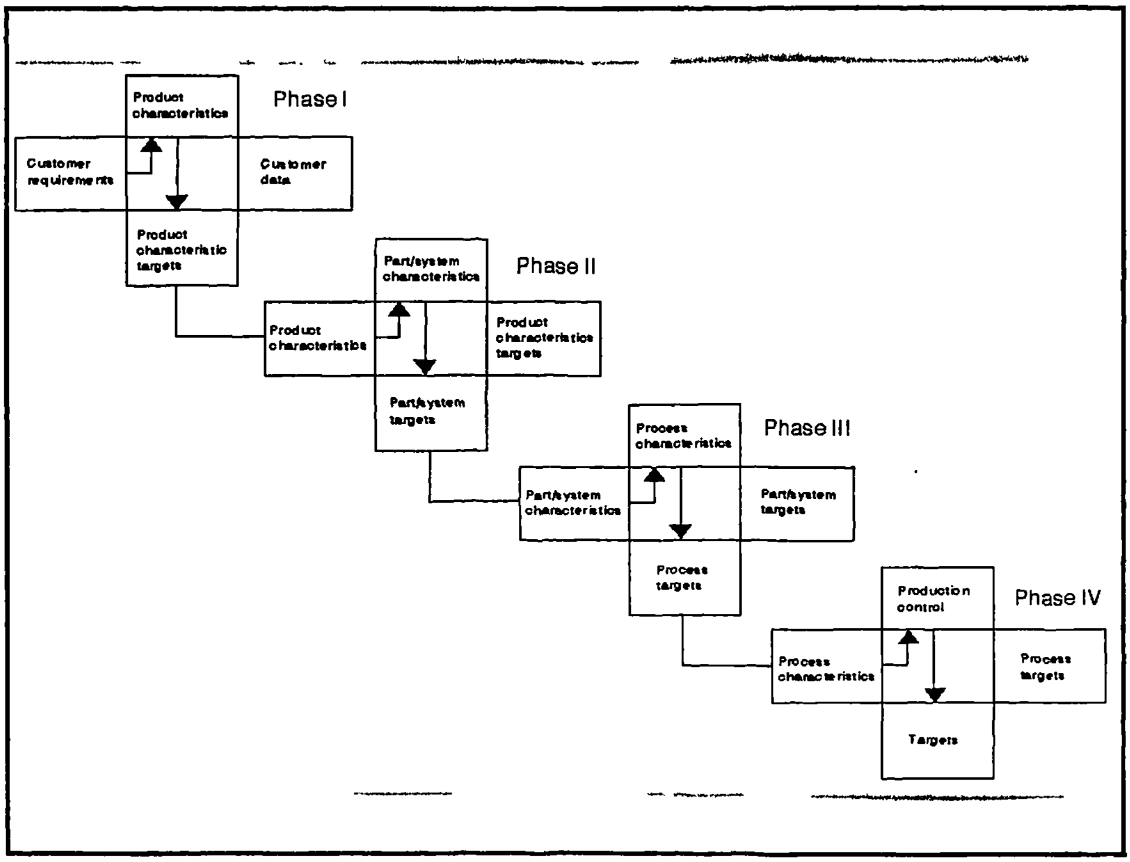


Figure 3.3 ASI approach to QFD.

Conceptually this approach is extremely useful as it allows those working on the manufacturing floor to understand the impact of what they are doing on the satisfaction which the customers will experience with the product. However due to step-wise implementation of the matrices, the approach may be wrongly interpreted by potential users as validating serial as oppose to concurrent product development process. This being the case, the negative effect is that many of the downstream issues failed to be addressed in the up-front design of the product. Hence the cost and time savings originally anticipated may not be materialised.

3.6.2 GOAL/QPC Matrix of Matrices Approach

The GOAL/QPC approach emphasise QFD as a planing tool within the total quality management philosophy. The approach uses matrix of matrices (Figure 3.4) as a means of translating the customer's requirements [138]. The approach differs from that of ASI in

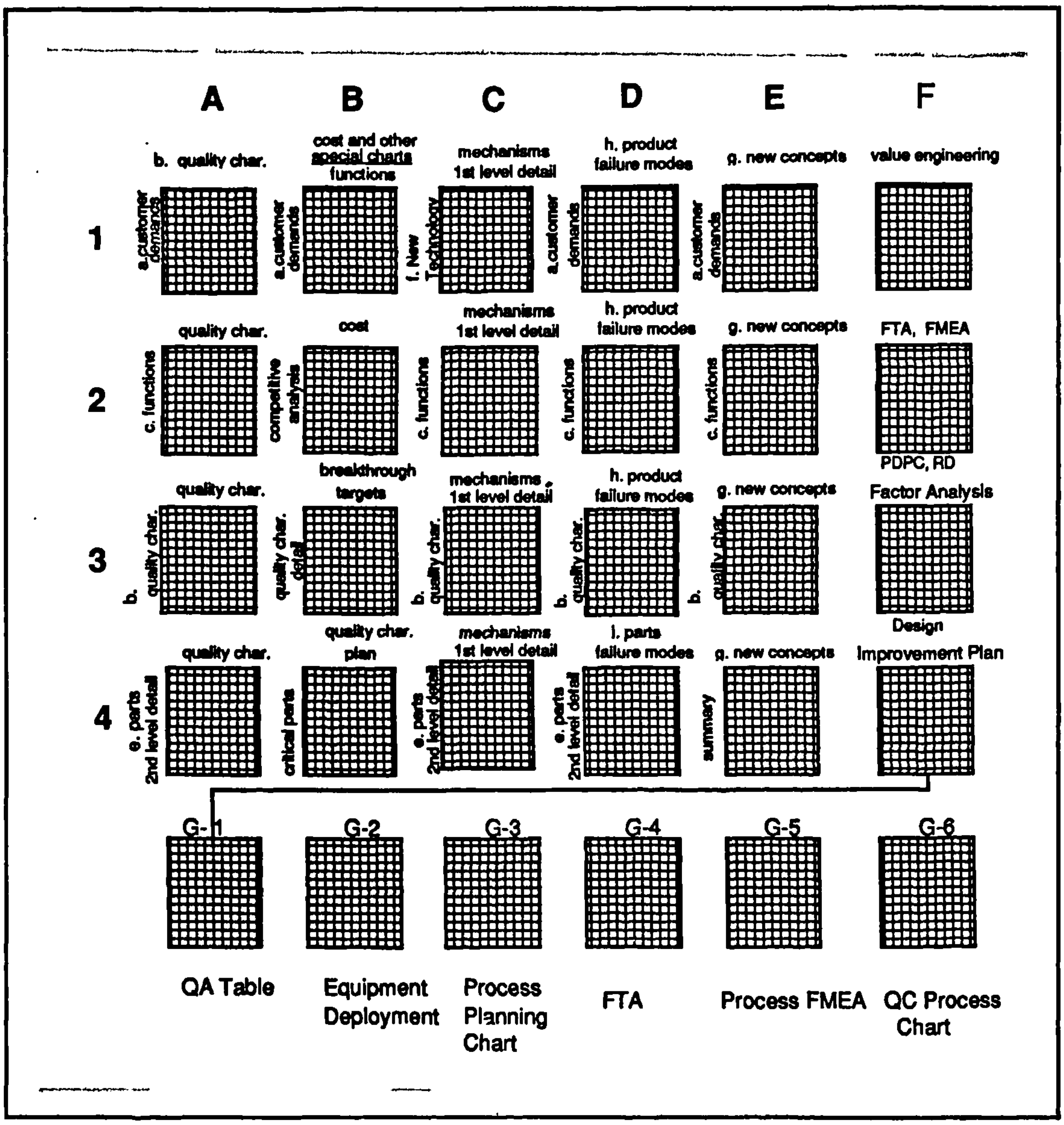


Figure 3.4 GOAL/QPC matrix of matrices [138].

that it includes additional deployments that were absent in the original Akao's (ASI) version of QFD, such as technology deployment, cost deployment, and reliability deployment. The new concept selection method is incorporated within the set of matrices instead of being left as an option in the ASI's approach. The issues covered by the matrices of this approach include: listening to the voice of customer; improving horizontal communication; prioritising improvements; targeting cost reduction; targeting reliability; targeting engineering breakthroughs; orchestrating engineering breakthroughs; improving communication between design and manufacturing; and process reliability. In the actual application, practitioners can pick and choose the charts that will help them with the real problems or in implementing particular company strategies.

Although this approach presents a detailed account of how to go about implementing QFD, it may appear intimidating to first time users due to its having large number of matrices. The absence of process guidance makes it conceptually difficult to follow.

3.6.3 International TechneGroup Incorporated (ITI) Approach

The third approach to QFD was developed by the International TechneGroup Incorporated (ITI) which emphasises the whole process of developing and producing a product efficiently in concurrent engineering environment [120] In this approach the QFD process starts with a business and market analysis to determine which product should be developed and why. It then evaluates the requirements from both internal and external customer in order to ensure that the resources of the company are correctly focused. This is schematically shown in Figure 3.5.

The advantage of this approach is that it explicitly addresses the QFD implementation in a concurrent engineering environment. The customer (external) requirements are integrated with internal requirements such as engineering requirements, business requirements and operations requirements. The selection of a product or process concept is only performed when all requirements have been converted to measurable product/process characteristics. The mechanism described provides a good approach to get all departments to be involved in the project early, and it acts as a means of tying the strategic planning process into product development.

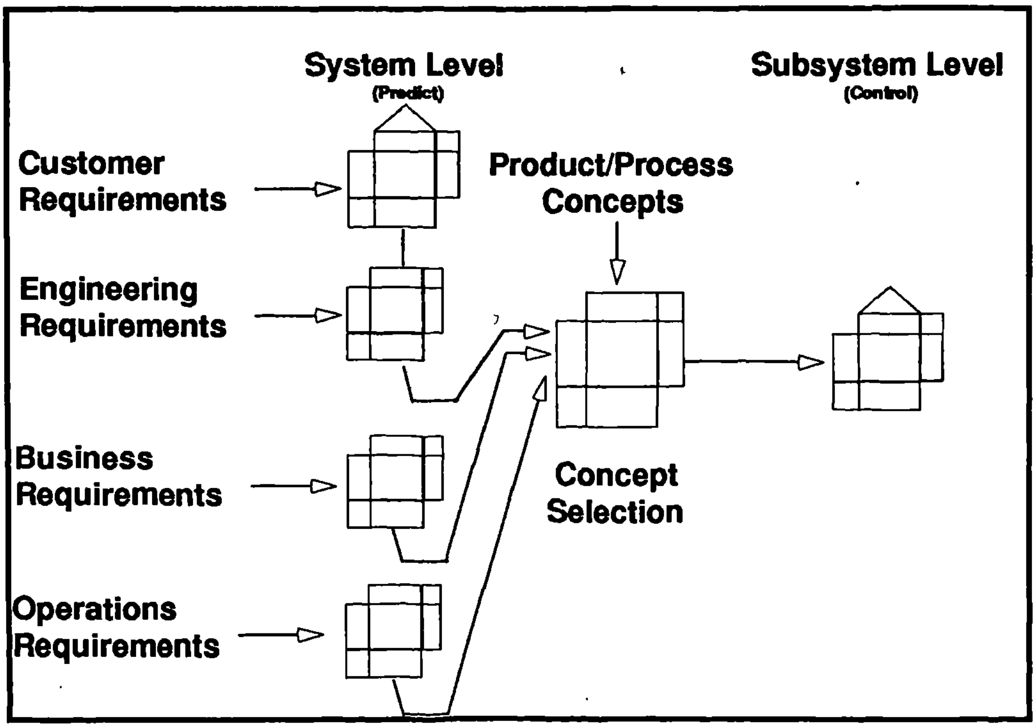


Figure 3.5 ITI approach to QFD [120].

3.7 The Key Benefits of QFD

Increased customer satisfaction

- The methodology allows the injection of the voice of customers into the product/process development. QFD is claimed to be the most complete and convincing method for planning the goals of a stream of processes to align them to the final requirements of the stream, so that they meet the customer requirements [54].

Improved communication

- Provides a visual display of relationships between planning and design data using the matrix format. The interlocking relationship structure allows the complex inter-relationships of inputs and outputs to be more understandable.
- .Provides methods of verifying that the various design issues have been addressed. The requirements at subsequent levels of translation (deployment) can be tied back to the basic customer wants. QFD has been used, for example within the framework of integrated engineering approach in Lucas Systems and Engineering [180], as a structure to provide guidance for team activity and simultaneous engineering.
- Design and development efforts can be prioritised and tasks and functions are only performed when driven by customer needs.
- The process develops cross-functional teamwork which enhances effectiveness and reliability. Misinterpretation of program objectives, marketing strategy, and critical control points can be avoided, thus minimising the need for change.

Better documentation

- The use of matrices allows the complex sets of data to be easily prioritised and arranged in logical relationship. It makes it easier for the design team to see what needs to be done.
- When linked together the charts create a design knowledge base which shows the flow of information from the voice of the customer to product objectives to engineering specifications to process parameters to operator instructions and shop floor control plans.

Reduce time to market

- Reduces design and development time. The key to shortening the overall design time is to better define the product and better document the design process. This improves the efficiency of the initial design and drastically reduces the need for redesign [138]. The QFD approach expands the time taken to define the product, as shown in Figure 3.6.

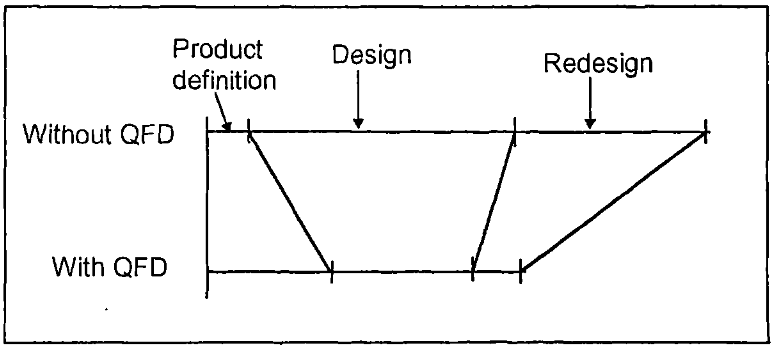


Figure 3.6 The impact of QFD in design time reduction [138].

- Reduction in design changes/problem solving, thus resulting in fewer start-up problems. QFD promotes preventive rather than reactive development of product, i.e., quality checks are moved upstream. Changes made prior to production are less expensive because they are made on paper.

3.8 Comparison With Other Planning Methods

3.8.1 QFD and Systems Engineering

The concepts presented in QFD are not substantially different from that of systems engineering. It has been regarded as an outgrowth of systems engineering shortcomings [234]. In the basic systems engineering approach, requirements flow down from system to component level and then products are developed from components up to the complete system, as shown in Figure 3.7. Two essential elements of systems engineering which are also applicable in QFD are: comprehensive definition of requirements at all levels, and not attempting higher level integration until development is complete at lower levels. However systems engineering differs from QFD in that,

- the primary focus of systems engineering is generally the product and its requirements rather than the process by which it is produced,

- outputs at component through system level are the major objectives, and not much attention is given toward understanding interrelationships, and
- the requirements in the systems engineering approach are generally developed by responsible engineers and therefore represent the 'voice of the engineer', which may not reflect the 'voice of the customer'.

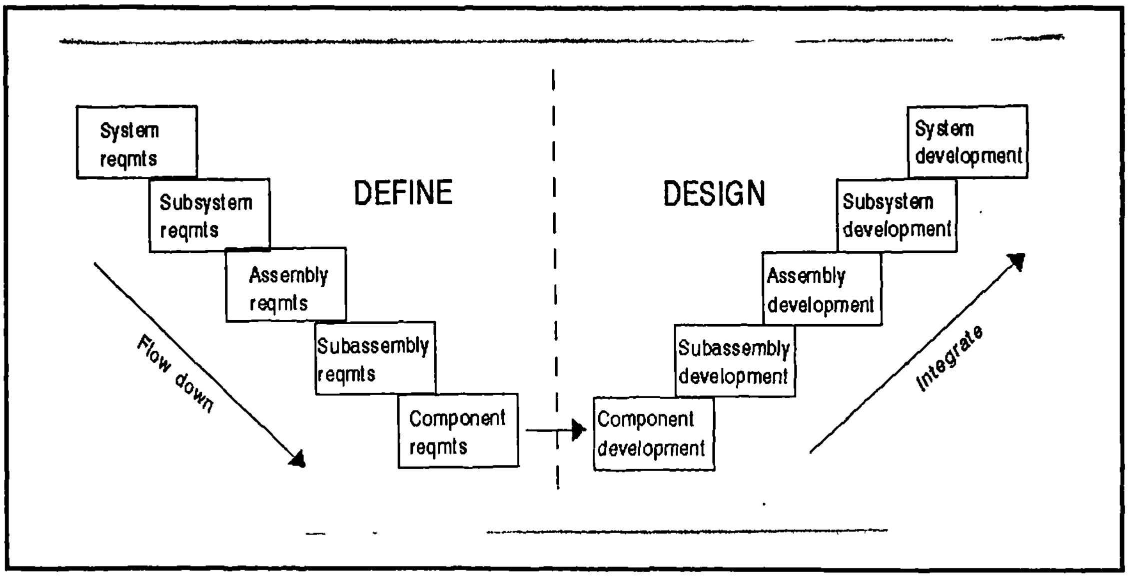


Figure 3.7 Systems Engineering model.

3.8.2 QFD and Juran's Quality Planning

Juran [125] develops Quality Planning as a method for building quality into products and manufacturing processes. The method is based on the premise that manufacturing enterprises face losses and waste due to three factors - quality of the competition, poor product quality, and threats to society. To assist manufacturers manage for quality, the quality planning road map has been developed, Figure 3.8. The boxes in Figure 3.8 represent method activities and the links between the boxes represent the method deliverables. Although quality planning and quality function deployment appears similar methodologically, they differs in terms of their emphasis on phases and deliverables.

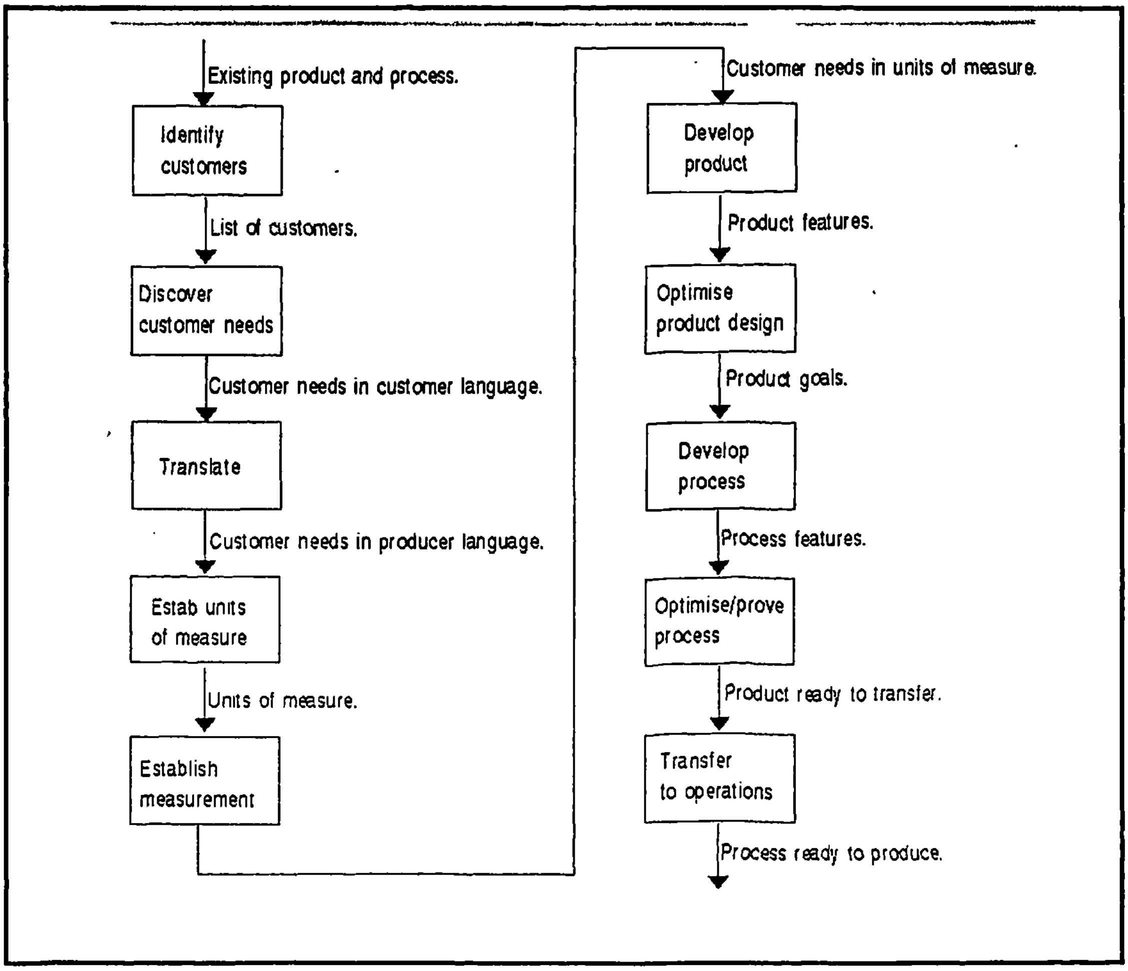


Figure 3.8 Juran's Quality Planning [125].

In quality planning measurement plays an extensive role throughout the process as all objectives need to be quantified. The method does not assign significance to the prioritisation of customer needs. In it lacks emphasis on teamworking as evident from Juran [125]: ' The quality planning may be done by product designers, quality specialists, operating personnel, or some combination of personnel in all these categories.' On the other hand, QFD concentrates on maximising customer satisfaction by seeking out both the spoken and unspoken needs. It also allows customers to prioritise their requirements. The methodology provides a more coherent and efficient structure to communicate what matters most to the customer. Organisational resources are then aligned behind these critical requirements.

3.9 The Use of QFD in Non-product Applications

The scope of application of QFD has expanded beyond that of product design and development. The technique has been customised and integrated with other management techniques. Examples are given from construction, process, service, and software development applications [4]. Mazur [176] provides an extensive discussion and examples on the use of QFD in the service industries. QFD have been used in conjunction with Ishikawa chart and value analysis in a conceptual methodology for tool/method selection in concurrent engineering [130]. The 'customer' in this case is not the traditional end product user, but rather the individuals responsible for the particular design function being evaluated. Dale and Best [59] report the use of QFD to assist an investment programme for replacement of plant and equipment. Chang [43] proposes a general design of an integrated total quality information system involving QFD processes. Data flow diagram is used to illustrate the structure of the information system.

Gopalakrishnan et al., [95] utilise the house of quality to improve the quality of internal processes by establishing 'customer-supplier' links within the organisation. The procedure consists of six steps: (1) determining product characteristics; (2) rating the product characteristics; (3) determining supplier performance variables; (4) evaluating supplier performance; (5) determining relationships between performance variables; (6) setting performance targets. The 'product' in this case could be the actual product being manufactured, or the service rendered from one department to another.

Sullivan [259] introduced the application of QFD in policy management, which is a strategy to ensure results by focusing on the means as oppose to measuring performance. The use of QFD in business planning has been reported in [62]. The objectives of business planning are to achieve goals through a comprehensive planning process across the whole organisation and to reduce the gap that exists between departments. In this application of QFD the first matrix translates the vision of the company as 'the voice of the organisation' into objectives which represent how the organisation intends to accomplish its vision. Table 3.1 summarises the contents of the planning matrices.

Planning matrix	WHATS	HOWS
# 1	Vision	Objectives
# 2	Objectives	Strategies
# 3	Strategies	Action plans
# 4	Action plans	Responsibility

Table 3.1 QFD in business planning [62].

In the field of academia, QFD has been used to identify key customers for an academic department research efforts [45], and the design of engineering curriculum [147]. QFD has also been implemented in industrial research and development [166].

With regard to the use of the QFD concepts in manufacturing system design, there has not been any specific published article on the subject. The nearest description of such application is by [59], in which the back-end matrices of the technique have been used to assist an investment programme for plant and equipment.

The above discussion has shown that when applied in its broadest sense QFD can help improve business operations in general, in addition to its original intended use for product design and production enhancement. QFD is thus a versatile technique that can be employed to address a wide range of business and organisational situations requiring decision making in a multitude of criteria, requirements or demands.

3.10 Variations and Extensions of the QFD Method

Besides the development of the three approaches mentioned in Section 3.6, further enhancements and refinements to the basic conceptual framework of QFD have also taken place. The voice of customer table has been developed at the front end of QFD to provide an edge to the technique [175]. It is a two-part tool to provide structure and process for seeking out that the true needs of the customer is identified. Using the competitive customer assessment information contained in the QFD planning matrix, Wasserman, et al., [278] derived a method of constructing an overall customer satisfaction index. For raw customer data which is too qualitative, the fuzzy set theory is used to convert linguistic information to their corresponding fuzzy numbers.

Noting the fit between the structure of product planning matrix and the rule-based paradigm for expert systems, a network of knowledge bases has been proposed to support the QFD method [32]. This application is extended by developing object-based architectures for the design of expert system to support quality management activities based on QFD and quality planning [24].

When QFD is applied to general business decisions involving multiple options on action selection, a consolidation factor (CF) is introduced to enhance the option selection process by allocating credit to decision option in proportion to how each addresses all specified criteria in conjunction with total weighted relationship [281]. Thus the CF reflects the number of criteria addressed by a particular option relative to others for a better decision. In dynamic QFD [1], a feedback loop is incorporated from customers to the firm in order to continuously improve customer satisfaction over the product life cycle.

3.11 Summary

Quality Function Deployment is an effective methodology that can ensure the requirements of the customer and the market as a whole on the quality of products or services are met during their design and development. With the use of planning matrices a mechanism is provided to ensure product quality and manufacturing effectiveness, even before design becomes a reality. The ideas and techniques contained within QFD are not new. What is new about QFD is the way these ideas and techniques are integrated into a system, which when followed, will structure the work as a whole. A series of steps are provided so that design teams can follow to get their job done more effectively.

Based on the basic framework of the methodology, QFD has been used in numerous applications for product design and development. Its versatility and potential as a planning and design support tool is evident from the fact that more projects on non-product applications are being reported. Although most of the cases reported are involved in the deployment of quality function, the flexibility of the approach can be extended so that other functions can be deployed. However such deployments must conform to the conceptual framework that has been outlined in Section 3.3.

With regard to manufacturing system design there is much scope to be explored on the use of QFD concepts in this area as there appears to be no published work.

CHAPTER 4

MANUFACTURING SYSTEMS DESIGN SURVEY

4.1 Introduction

It has been reported in numerous literature that the sophisticated technological developments in the domain of computer-integrated manufacturing such as CAD, CAM, FMS, MRPII and robotics systems promise to offer significant strategic benefits in terms of increased competitiveness [122, 189, 214]. Measures of the competitiveness include performance efficiency, quality, cost reduction and greater economies of scope. Due to the complexity of these technologies and their high investment cost, manufacturing systems comprising these technologies must be planned and designed so as to bring about successful implementation. Two levels of success have been defined, firstly that of technical success in terms of operational effectiveness, and secondly the realisation of the expected benefits or business success [276]. The design and planning of advanced manufacturing systems should minimise the uncertainties [31] and address related problems such as [195]: the equipment-supplier relationship, the fit between products and production processes, the fit between the process and manufacturing strategy, the education and training of personnel, the integration with other support systems, the commitment and support of top management and the pace of adoption.

In order to achieve the full potential of the advanced manufacturing technologies, they must be introduced and implemented effectively. Various design methodologies and tools have been developed to facilitate the planning and design of manufacturing systems. The detailed review has been presented in Chapter 2. What has been evident from the literature was that there was no lack of published articles on the application of the design methodologies and tools. However no significant literature was identified that showed the comparative analysis of the various design methodologies and tools. In terms of industrial perspective, the discussion held during the industrial visits tended to suggest that the level of awareness of the design methodologies was not substantial. Due to the nature of the information required, and the lack of previous research, a decision was taken that a survey should be conducted.

This chapter discusses the planning and the findings of an industrial survey which has been carried out on a selected sample of UK manufacturing industry. The postal questionnaire was used as the survey instrument. In order to optimise the use of time and resources a proper planning and implementation of the survey needed to be carried out. The following stages were involved:

- Definition of the aims and objectives.
- Identification of the information to be gathered.
- Identification of the population.
- The design of the questionnaire.
- Data collection.
- Processing and analysis of the information obtained.

4.2 Planning of the Survey

4.2.1 The Aim of the Survey

The aim of the survey is to investigate the general trends of industrial practices in the approaches to manufacturing system design. In particular the study is intended to identify the nature of relationships that exist between manufacturing strategy and manufacturing system design decisions. The influence of the competitive priorities of manufacturing strategy in the realisation of the physical implementation of the manufacturing system will be given consideration. The characteristics and the extent of application of manufacturing system design methodologies and tools will be investigated. These are to be achieved by collecting the primary data from a sample of manufacturing industry, with the focus on those companies which are involved in metal machining processes. The processing and analysis of the results is facilitated by the use of the statistical package, SPSS/PC+ [86]. Descriptive statistics methods will be used in the analysis and discussion of the results.

4.2.2 The Questionnaire Design

The questionnaire survey is an effective method of gathering information by directly asking the people in the sample. The first step in writing a questionnaire is to identify exactly what kind of information is desired from the survey sample. To meet this requirement two approaches have been adopted: (1) extensive literature search was performed on the types of manufacturing systems and the parameters that affect their configurations, as well as on the planning and design methodologies and tools that have been developed; (2) visits were made to machine tool manufacturers and users of manufacturing systems. Chapter 2 provided an extensive review of the findings of the first approach, while Appendix C lists the companies visited.

Taking into account of the discussions and observations made during the industrial visits, as well as the information obtained from the literature, the questionnaire was specifically designed in order to achieve the following objectives:

- to characterise the development and performance of the existing manufacturing systems,
- to investigate how and to what extent the deployment of competitive advantages in manufacturing system design and development,
- to study the parameters that affect decisions at various stages of manufacturing system design,
- to identify the methodologies and tools employed to support manufacturing system design, and
- to gauge the degree of effectiveness of the methodologies and tools that have been used.

In order to obtain information on the above issues the questionnaire was conveniently divided into two sections (Appendix D): items that relate to the development and performance of the manufacturing systems, and items that relate to the application of the design methodologies and tools.

4.2.2.1 Information on the Current Manufacturing System

The aim of this section is to glean information on how manufacturing systems of the companies surveyed have developed and to assess what major factors or parameters that affected the design decisions on the various system configurations. Respondents were also asked to what extent the manufacturing systems have been effective in attaining the stated objectives. This is measured in terms of the achievement of a set of performance measures. In order to set the information provided in proper context, the companies were also profiled in terms of size, type of manufacture and nature of products.

4.2.2.2 Manufacturing Systems Design Methodologies and Tools

The second part of the questionnaire concentrated on the approaches that have been taken in designing manufacturing systems. As discussed in Chapter 2, the need to gain the competitive edge requires the manufacturing companies to have a clear manufacturing strategy which must be related to the tactical decisions of technology selection. Hence, items in the initial part of Section B of the questionnaire were related to this issue. The significance of the economies of scope, or flexibility in the design of manufacturing systems was also addressed in the questionnaire. Respondents were asked what methodologies and tools had been used at the various stages of design, and how effective have they been. The design stages that have been identified were requirements analysis, conceptual design/specification, detailed design, and technical evaluation and selection. The effects of these methodologies and tools on design process were also studied. Finally questions were posed on the constraints and limitations faced by the companies during the design and development of advanced manufacturing systems.

4.2.3 The Survey Population

The survey population consisted of manufacturing companies in the U.K. In this survey the selection of the sample was based on the main criterion that the manufacturing firms are involved in some form of metal machining activities. This sampling frame was used in order to ensure that a certain extent of advanced manufacturing technologies are implemented.

Extensive reference was made to the Directory of Key British Enterprise [73]. The main reason for choosing this directory instead of other references such as the KOMPASS was that the Directory of Key British Enterprise provides information on Britain's 50,000 companies in decreasing order of size. The companies are ranked both in terms of the value of annual turnover and the number of employees. This serves to facilitate the selection of appropriate companies in the sample. In addition to the nature of products manufactured and the processes used, the value of turnover provided a good measure of the capability of the firms to invest in advanced manufacturing technologies.

The questionnaires were administered to 250 selected manufacturing companies within the industry sectors that include metalworking, mechanical engineering, machine tool manufacturing, automotive, electrical and electronics engineering and household consumer goods. This selection was based on the assumption that some form of metal manufacturing activities are involved. The sample companies conform to the main industrial groupings of the United Kingdom Standard Industrial Classification (SIC) within the division of metal goods, engineering and vehicle industry, see Appendix E. It was impossible to ascertain the exact population in this category. However the survey sample was deemed sufficient based on a study on similar type of sample [118, 163]. In addition it was suggested that a survey which was to function as a preliminary investigation to search for general indications generally did not require a large sample [292].

4.2.4 Data Collection by Means of Questionnaire Survey

The information to be gathered by means of a postal survey offers many advantages such as the ability to investigate problems in realistic settings, the reasonable cost incurred in relation to the amount of information gathered, the speed at which it can be implemented and the reduction in the number of non-contacts. In addition the method allows respondents to make considered replies, with consultation of their records where necessary.

The technique of postal survey, however, has a few inherent limitations. These include the inability of manipulating independent variables as in laboratory experiments, the inappropriate wording and placement of questions within a questionnaire can bias results, the failure of obtaining an adequate response rate, and answers have to be accepted as final, as there is little opportunity for clarification of ambiguous answers, or appraisal of the validity of the responses by observation. The main problem, however, with most postal survey is that of obtaining sufficient response rate.

4.2.5 Strategies for Increasing the Response Rate

The effect of non-response is not only in decreasing the sample size, but it also introduces bias into the sample as non-respondents may differ from respondents. Although checks can be made on the representativeness of the sample, the best way to avoid bias is to reduce non response to a minimum.

Two reasons why non response occurs have been suggested: failure to contact the sample respondents, and refusal of the sample members to participate in the survey [123]. Both of these factors were taken into consideration during the planning stages. In order to reduce the problems and at the same time increase the response rate, attention was given and action was taken with regard to the following [65]: sponsorship, length of the questionnaire and the subject matter, format and layout, and the covering letter.

Although pretesting is the best way to discover whether the questionnaire is adequately designed, it is more suitable for a reasonably large population. Since the population for this study is relatively small, this method was found to be inappropriate. Hence, alternative way of improving the questionnaire was conducted:

- a face-to-face interview with a user of manufacturing system and a consultant involved in projects relating to manufacturing system design, based on the questionnaire,
- extensive consultation with project supervisor,
- distributing the questionnaire to the academic staff and research colleagues in the department for their comments and suggestions.

The issues covered include whether the questions were easily understood and simple to answer, the length of the questionnaire, as well as the format and layout.

4.2.6 Sources of Error

Errors can occur at almost every stage of the survey process. They can be classified as sampling or standard errors, measurement error and random error [123]. Sampling error occurs when measurements taken from a sample do not correspond to what exists in the population. Non sampling errors consist of response errors and errors made during the analysis.

There are four different reasons for sampling error to occur: (1) Missing elements as a result of inadequate definition of the sample, or the sampling being incomplete; (2) Clustering of elements represented as one element, such as the many large companies which can be broken down into many autonomous business divisions; (3) Companies may have moved on or gone out of business and thus may not be part of the frame; (4) The existence of duplicate listing of companies. In order to overcome these problems it was important to select a comprehensive and up to date sampling frame. In this case, the latest edition (1993 edition) of the Key British Enterprises Directory was used.

Response errors could occur through misinterpretation of questions or mistakes in completing the questionnaire. In order to minimise the errors, steps were taken to ensure that the questionnaire was laid out in a clear manner with no ambiguities. Where possible the questionnaire used coded answers and only in several cases written answers were required. Another possible source of error could occur in the tabulation and analysis of data. Although mechanisms were built in the computer package to detect some of these errors, extreme care was taken to ensure the correct values were entered.

4.2.7 Processing and Analysing the Data

When the questionnaires were returned they were checked for missing values or obvious errors. Questionnaires with significant amount of information missing were discarded. The data was analysed using the software package SPPSX/PC+ (Statistical Processing for the Social Sciences, Version 5.0.1) in the PC laboratory. The package was chosen as it was readily available and ideally suited to the analysis of the survey data.

4.3 Survey Findings

4.3.1 Response Rate

A total of two hundred and fifty questionnaires have been despatched to a selection of engineering companies that are involved in discrete parts manufacturing. From this target sample thirty nine questionnaires were returned. However eleven were not usable because of missing data. This represents an overall response rate of 11.2 percent. Eight firms declined as a general corporate policy to not participate in mail survey studies, and five were returned by the postal service marked as undeliverable. The majority of the questionnaire were received well within the stipulated returning date.

4.3.2 Description of the Sample

4.3.2.1 The Respondents

The questionnaire was addressed to the managing director of each company, with a covering letter asking him/her to forward it to the appropriate person. Table 4.1 shows the distribution of the job titles of the respondents. From the usable responses, one did not provide the required information on the job title.

Job title	Percentage (N=27)
Managing Director	14.8
Manufacturing/production Manager	59.3
Logistics/materials Manager	11.1
Quality/business quality Manager	7.4
Production Control Manager	7.4

Table 4.1 Type of respondents

Analysis of the table indicates that the majority of the questionnaires were completed by manufacturing or production managers who were assumed to have had some role in the process of design and development of the manufacturing systems. This is significant with respect to the validity and accuracy of the information provided. In cases where the questionnaires were completed by the managing director, it was found that the companies are relatively small, indicated by the annual turnover and the number of employees. Respondents with other job titles are included in the group with the closest description. For example, Chief Executive Officer is categorised as Managing Director, and Works Manager is put under Manufacturing Manager.

4.3.2.2 Type of Company

The type of companies represented in the sample are shown in Table 4.2. This analysis is based on the classification of the sampling frame. The survey was dominated by responses from the mechanical engineering and manufacturer of motor vehicles and parts thereof. This was expected as those companies in turn dominate the manufacturing sector itself. It was the intention of the questionnaire to examine companies from the sector which was likely to have some form of discrete part manufacturing facilities, and in turn involved in advanced manufacturing.

Category	Percentage (N=28)
Mechanical engineering	50.0
Automotive and parts thereof	21.4
Electrical and electronics engineering	10.7
Instrument engineering	10.7
Other transport	3.6
Office machinery and data processing	3.6

Table 4.2 Type of company

4.3.2.3 Company Size

Company size is normally measured in terms of the number of employees and the annual sales turnover. However in this research, the turnover value provides a more significant indicator of the company's ability to invest in advanced manufacturing technologies. It was found for example, that the cost of implementing the flexible manufacturing systems ranged from £0.5 million to nearly £12 millions [163]. Furthermore the high level of automation involved is expected to reduce the requirement for worker. Hence the number of employees may not give the true picture. The range of company sizes in terms of the annual sales turnover is shown in Figure 4.1. The figure shows that although a wide range of companies were included in the sample, it was dominated by the medium size companies with annual turnover of 11-50 million pounds.

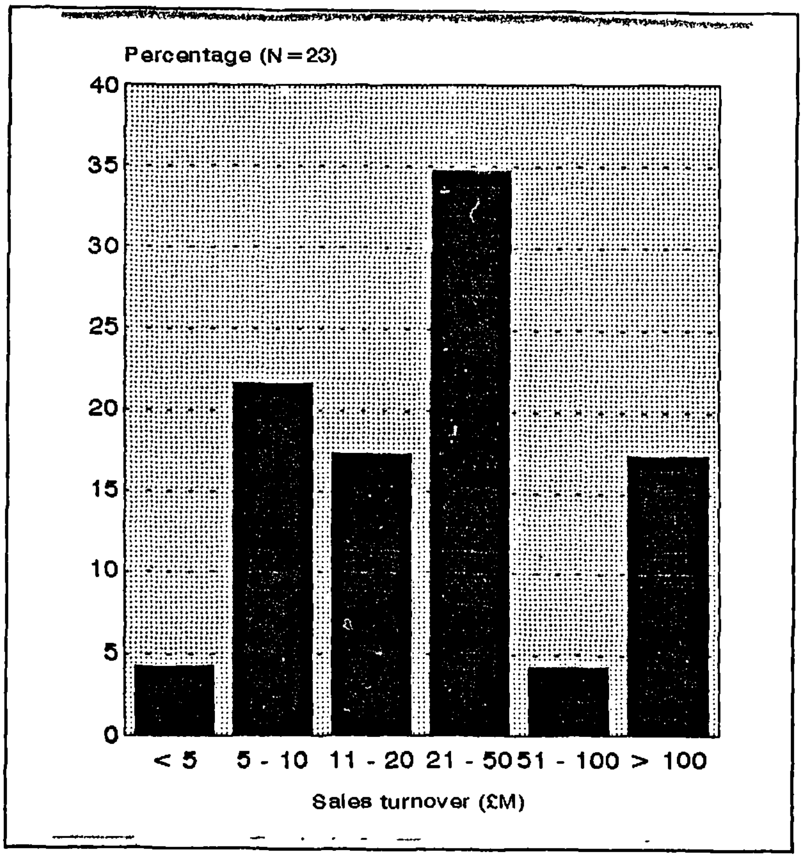


Figure 4.1 Annual sales turnover.

The information on the number of employees is given in Figure 4.2 in order to provide a complete picture on company size.

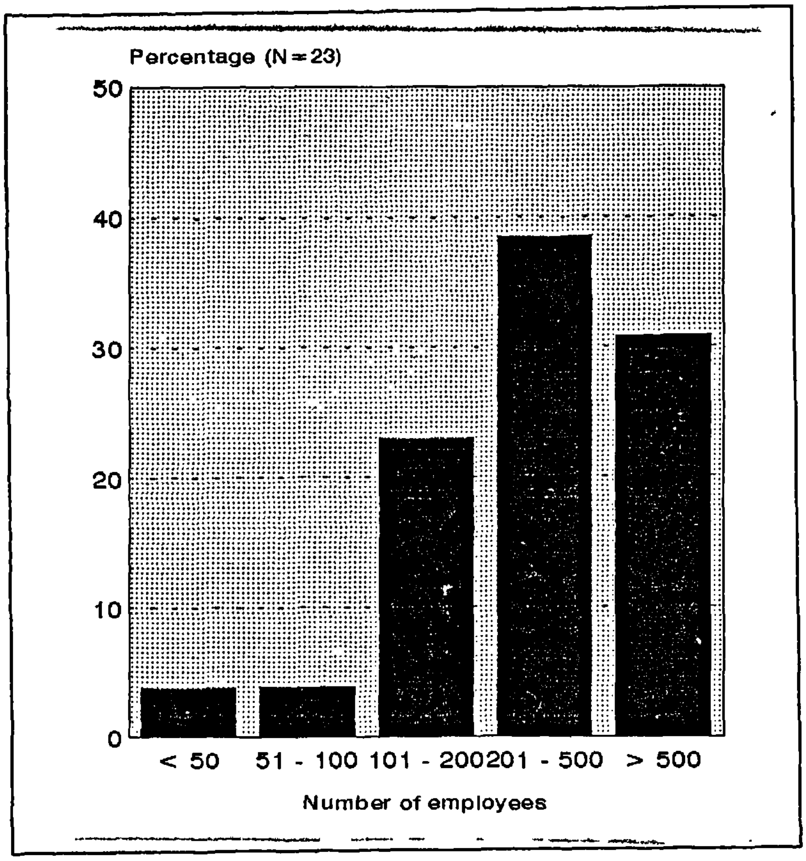


Figure 4.2 Number of employees.

4.3.2.4 Parts Produced

Figure 4.3 shows the range of different parts produced by the surveyed companies. In terms of the production rate, the respondents indicated the values of parts per hour which range from less than one (9%) to 100 (14%).This is shown in Figure 4.4.

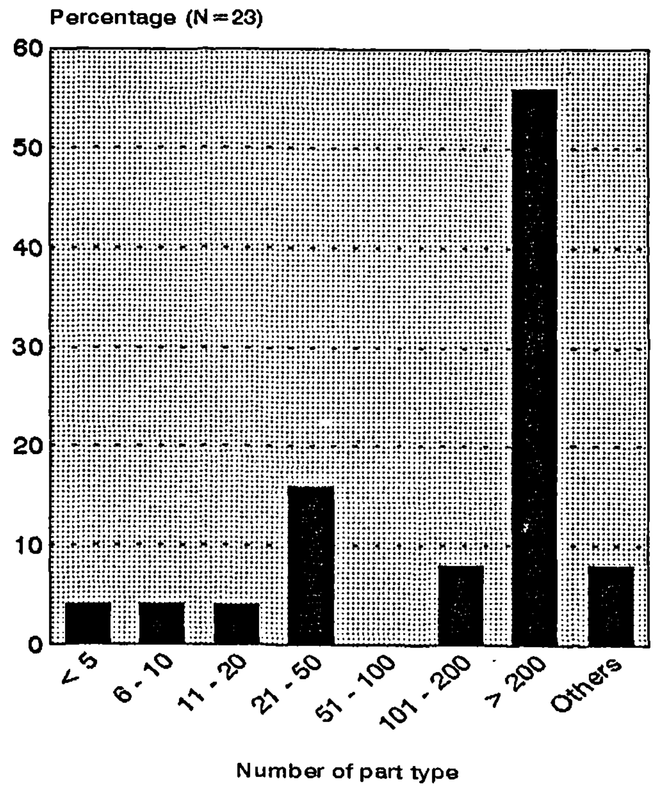


Figure 4.3 Number of part types produced by the sample.

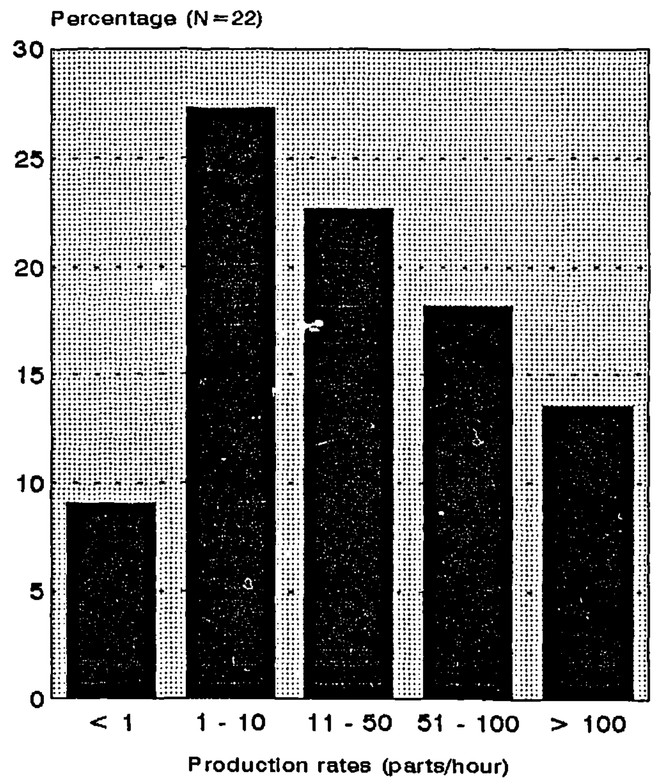


Figure 4.4 Production rates of the manufacturing systems.

4.3.3 Information on Manufacturing Systems

The questionnaire survey attempted to establish the current state of the manufacturing systems by gleaning information on the nature of manufacturing activities being carried out, the physical development of the facilities, the level of automation that has been achieved, the relative costs of implementation and the achievement of the systems in terms of their targeted performance. These issues will be catered for in the next six sub-sections.

4.3.3.1 Main Manufacturing Activities Performed

The range and type of manufacturing activities performed by the companies in the sample are shown in Table 4.3. The sum of the percentages add up to more than 100 since most of the respondents have more than one type of manufacturing activities employed in their system. The relative percentage of each type of manufacturing activity within the overall activities in the sample is shown in Figure 4.5. It is found that in terms of fabrication the majority of the respondents are involved in the machining of both prismatic and rotational parts.

Activities	Percentage
Rotational machining	71.4
Prismatic machining	57.1
Inspection	67.9
Assembly	92.9
Material handling	60.7
Others	39.9

Table 4.3 Types of manufacturing activities performed (N=28).

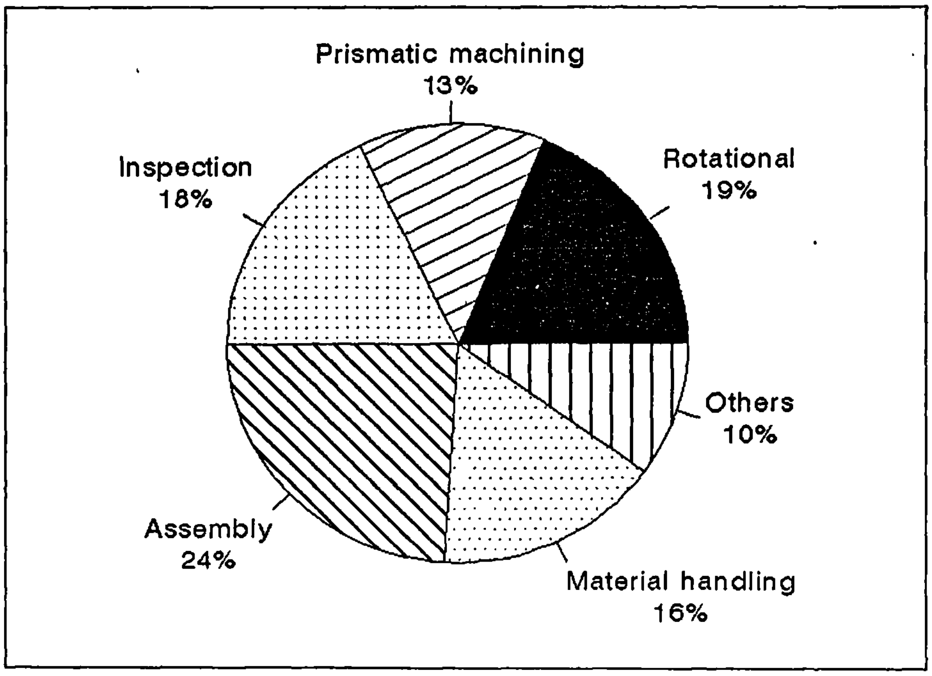


Figure 4.5 The relative distribution of manufacturing activities in the sample.

4.3.3.2 The Development of the Manufacturing Systems

There are many ways in which the manufacturing systems had been developed to their present state. The responses to this question seem to indicate that there are two main approaches that had been adopted by most responding companies: moving from isolated CNC machines into DNC link or CAD/CAM, and the pursuit of integration through the information flow, i.e., by the application of Manufacturing Resource Planning (MRPII). This is shown in Table 4.4.

Development of the manufacturing systems	Percentage (N=28)
Semi-automatic/automatic machines to CNC	21.4
Stand alone CNC to integration with CAD/CAM	25.0
From NC and CNC equipment into cellular layout	39.3
From cellular layout to FMS	7.1
Starting with computerised Manufacturing Planning and Control system	53.6
Initiating a totally automated greenfield site into FMS	0

Table 4.4 Development of the manufacturing systems

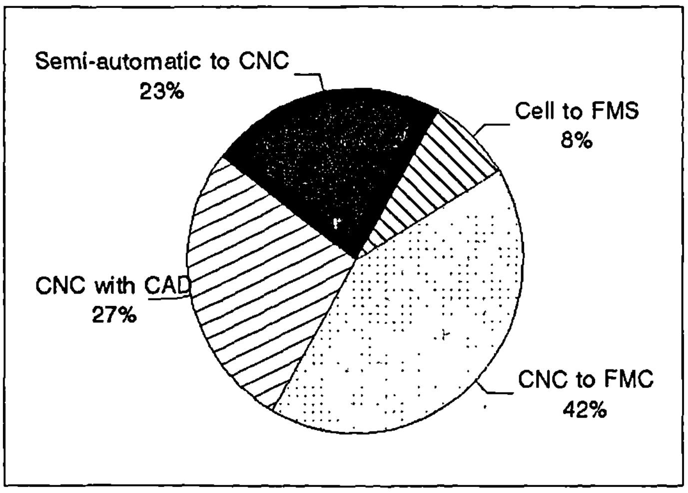


Figure 4.6 of Development of manufacturing systems in relative percentages

None of the respondents claim to have developed a full FMS from greenfield site, although about 7 percent did approach FMS via cellular manufacturing. Another feature of the developments is that many respondents indicated that they have pursued advanced manufacturing in more than one way. This is the reason for the total percentages to exceed 100. The relative distribution of the approaches is shown in Figure 4.6.

4.3.3.3 Category of Systems

Respondents were asked to identify their manufacturing systems with the typical designations that are used, i.e., based on the volume and variety parameters. The responses are shown in Table 4.5. It can be seen that the majority of the respondents considered their systems to be in the category of manned flexible cells.

Category of systems	Frequency (N=27)
Transfer line	11.1
Dedicated flow line	0
Flexible manufacturing systems	11.1
Manned flexible cells	55.6
Unmanned flexible cells	0
Job shop	22.2

Table 4.5 Category of manufacturing systems

4.3.3.4 Nature of Development

As shown in Table 4.6 more than three quarter of the respondents indicated that their manufacturing systems had been developed in-house.

Nature of development	**Percentage (N=26)**
Integrated in-house	76.9
Developed using turnkey system	23.1

Table 4.6 Nature of development of the manufacturing systems

4.3.3.5 Relative Cost of Implementation

With regard to the relative cost of implementation, a summary of responses is provided in Table 4.7. More than 60% of the respondents associated the cost of processing equipment to be more than 50% of the total systems cost. Forty five percent of the respondents indicated that the cost of information system and computer networking would occupy up to a quarter of the total cost. The cost of material handling equipment and inspection equipment are equally distributed but does not exceed 50%.

	Costs of sub-systems				
	less than 10%	10 to 25%	25 to 50%	50 to 75%	more than 75%
Machining equipment (N=21)	5.3	10.5	21.1	36.8	26.3
Material handling equipment (N=17)	47.1	41.2	11.8	-	-
Inspection equipment (N=17)	47.1	41.2	11.8	-	-
Computer networks(N=21)	30.0	45.0	15.0	10.0	-
Others (N=2)	100.0	-	-	-	-

Table 4.7 Relative costs of the sub-systems

4.3.3.6 Performance of the Manufacturing System

A measure of success in the implementation of advanced manufacturing systems can be defined along a few performance parameters. The companies were requested to indicate the performance of their manufacturing system. The measures used were: 1 for very poor, and 5 for very good. The results are summarised in Table 4.8. It can be deduced from the table that, in general, the respondents were satisfied with the achievement of most of the objectives of the manufacturing systems implementation. On average nearly half of the respondents considered the performance of their systems to be good or very good. For machine utilisation, only 11.5% of the respondents felt that the performance to be very good. In order to rank the performance, the percentage for very good is multiplied by 5, the next one by 4 and so on until the percentage for very poor is multiplied by 1[246]. The individual totals obtained by this multiplication are added for each performance. The resultant sum gives a measure of ranking of the performance achievement, as indicated in Table 4.9.

Performance	**Relative performance**				
	1	2	3	4	5
Lead time reduction (N=27)	3.7	22.2	22.2	22.2	29.6
Through-put time reduction (N=27)	3.7	22.2	22.2	25.9	25.9
Work-in-progress reduction (N=27)	3.7	11.1	29.6	29.6	25.9
Manufacturing cost reduction (N=27)	3.7	18.5	25.9	33.3	18.5
Product quality (N=27)	3.7	11.1	25.9	37.0	22.2
Machine utilisation (N=26)	3.8	19.2	42.3	23.1	11.5
Flexibility improvement (N=27)	3.7	11.1	37.0	29.6	18.5

Table 4.8 Performance of the manufacturing systems

Ranking	Performance	Value
1	Work-in-progress reduction	3.63
1	Product quality	3.63
2	Lead time reduction	3.52
3	Throughput time reduction	3.49
4	Flexibility improvement	3.48
5	Manufacturing cost reduction	3.44
6	Machine utilisation	3.19

Table 4.9 Ranking of manufacturing system performance

Table 4.9 provides an overall picture of the perceived performance of the manufacturing systems by the respondents. Reduction in WIP and improvement in product quality are the performance measures that were considered to be most satisfactory, whereas machine utilisation was considered poor.

4.3.4 Manufacturing System Design

4.3.4.1 Manufacturing Strategy

Respondents were asked to indicate whether they have a formal statement of manufacturing strategy. In terms of the presence (or absence) of manufacturing strategy, 70% of the respondents indicated that they have a manufacturing strategy, whilst 30% didn't have any.

4.3.4.2 Strategic Objectives to be Achieved

Strategic objectives represent a set of factors within the manufacturing strategy that each company wish to excel in order to be competitive. These are cost, quality, flexibility and delivery. The importance of these objectives to be considered in the design of manufacturing systems have been elaborated in Chapter 2. The respondents were asked to rank these factors according to the degree of importance to their companies. The results are shown in Table 4.10. It appears that even those that have indicated that their organisation did not have any formal statement of manufacturing strategy have responded to this question. This shows that even if a company did not have a manufacturing strategy as such, certain or all of the objectives contained within the strategy are pursued.

As can be seen, cost, quality and delivery appear to be most important to more than three quarter of the respondents. A greater degree of reservation in expressing the importance of flexibility is evidence as less than a quarter of the respondents considered that as the most important objective. This is contrary to what was initially expected, and represents a significant departure from what has been stressed by the literature on the importance of flexibility.

	1	2	3	4	5
Cost (N=27)	3.7	7.4	18.5	18.5	51.9
Quality (N=27)	3.7	0	7.4	37.0	51.9
Flexibility (N=25)	4.0	12.0	36.0	28.0	20.0
Delivery (N=27)	3.7	11.1	3.7	25.9	55.6

Table 4.10 The relative importance of strategic objectives (1=least important; 5=most important)

The ranking of the strategic objectives pursued by the sample is shown in Table 4.11. It can be seen that the gap between the first three objectives and flexibility is quite large. The difference between quality, delivery and cost is quite marginal.

Order of importance	Strategic objectives	Value
1	Quality	4.33
2	Delivery	4.20
3	Cost	4.08
4	Flexibility	3.48

Table 4.11 The ranking of importance for the strategic objectives.

4.3.4.3 Type of Flexibility

In order to establish further the significance of flexibility, respondents were asked which aspects of flexibility their companies were concerned with. The results are shown in Table 4.12. As discussed in Chapter 2, there are many types of flexibility associated with manufacturing systems. However in this survey, they are limited to the ones that are less theoretical, and more easily understood by the respondents. In any case option was given to the respondents to express any other flexibilities that they might have adopted. The total percentage is more than 100 since most of the respondents have more than one type of flexibility. Thus the values are rationalised and presented as a bar chart in Figure 4.7.

Flexibility aspects	Percentage (N=28)
Machine flexibility	61.9
Process flexibility	28.3
Product flexibility	60.7
System flexibility	42.9
Volume flexibility	57.1
Expansion flexibility	35.7
Others: Operator flexibility	3.6

Table 4.12 Type of flexibility pursued by the respondents (actual percentage for individual flexibility.

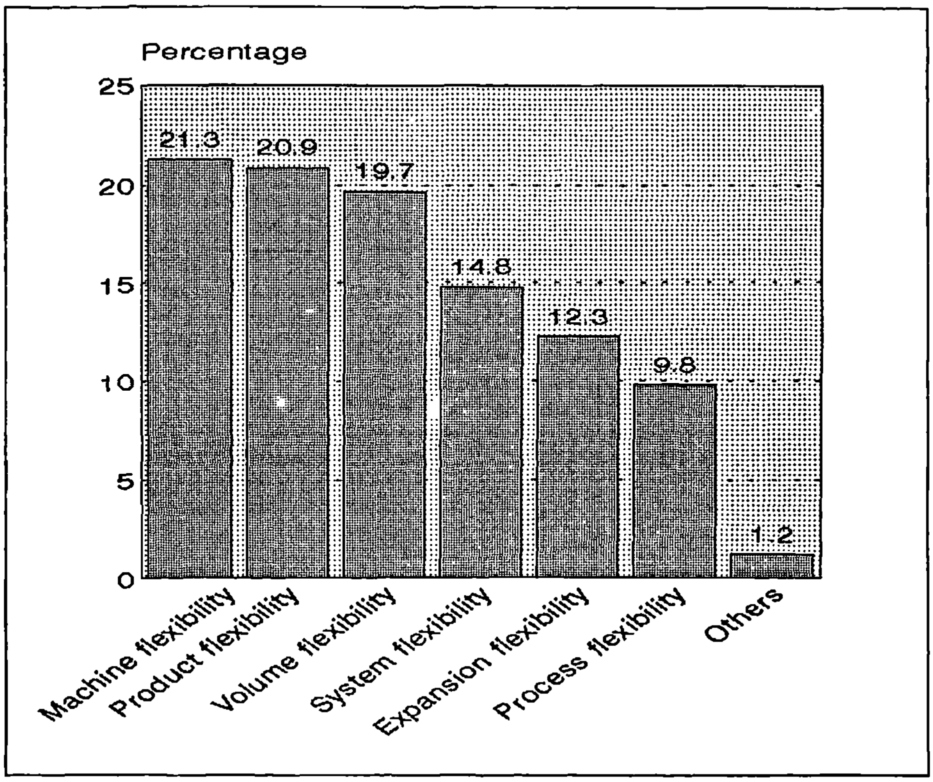


Figure 4.7 Type of flexibility (relative percentage)

4.3.4.4 Approaches to Flexibility

Respondents were asked how their companies approach flexibility. The results are shown in Table 4.13 and Figure 4.8.

Flexibility approach	Percentage
Use of flexible machine (N=27)	69.2
Improve flexibility of material handling (N=26)	7.7
Improve machine control flexibility (N=26)	38.5
Increase tooling capacity (N=26)	42.3
Having flexible routing/scheduling (N=26)	26.9
Adopting cellular system (N=26)	30.8
Introduce multi-skill workers (N=26)	42.3
Other approaches (N=17)	23.5

Table 4.13 Approaches to flexibility (actual percentage)

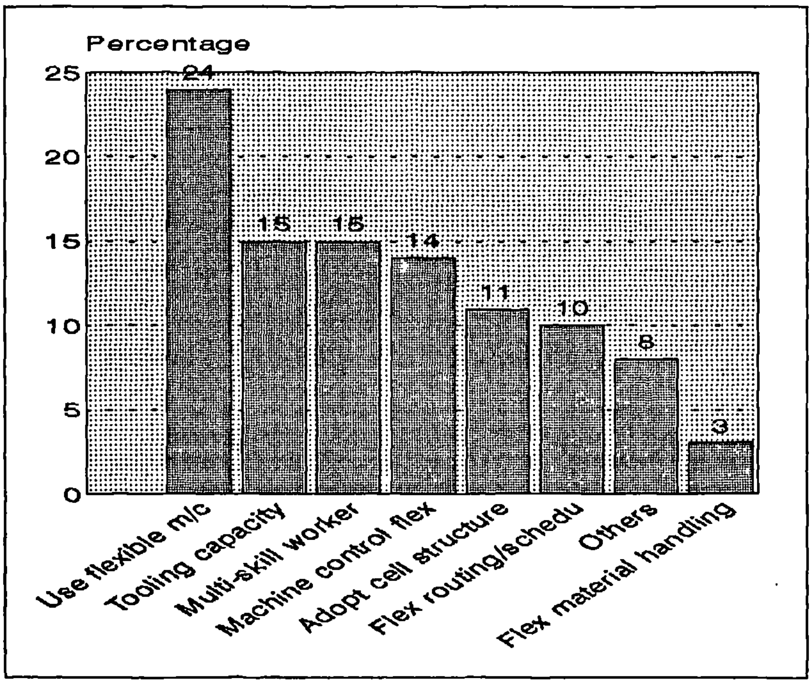


Figure 4.8 Approaches to flexibility (relative percentage)

Approaches other than those listed in the questionnaire have been cited by the respondents, and they cumulatively occupy a significant percentage, as shown in the bar chart of Figure 4.8. They include: personnel training, work redesign for teamworking, the provision of buffers, parts rationalisation and standardisation, and standby machines.

4.3.4.5 Aspect of Delivery

Another important competitive advantage that need to be considered in manufacturing system design is delivery. In this respect, respondents were asked to verify which aspect of delivery, i.e., delivery speed and delivery reliability that they considered to be most important. The results are shown in Figure 4.9.

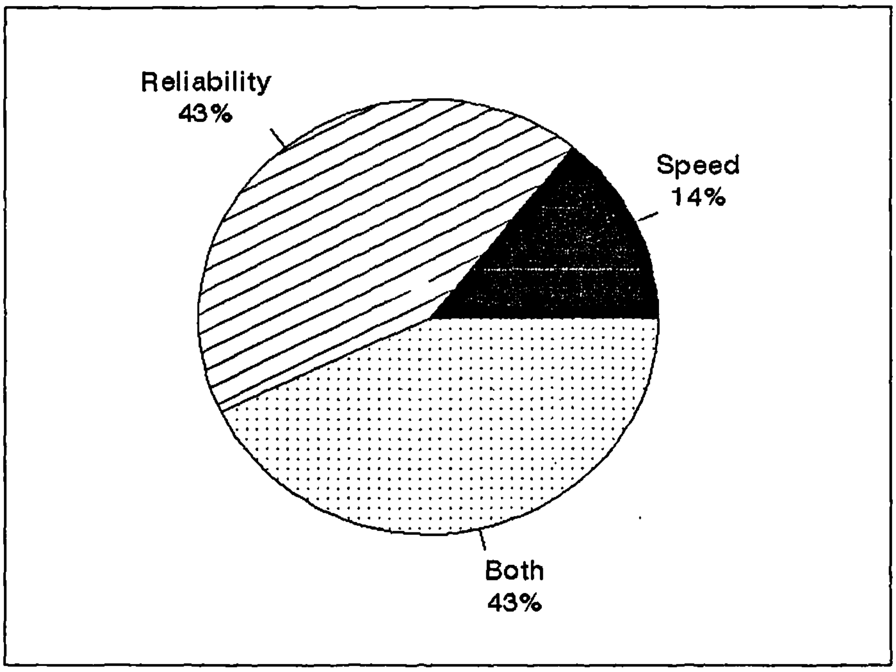


Figure 4.9 Important aspects of delivery

4.3.4.6 Frequency of Design/redesign.

The respondents were asked to indicate how often they undertake design/redesign activities. The results are shown in Table 4..

Frequency of design/redesign	Percentage
Every new product introduction (N=25)	8.0
Every time with major product modifications (N=25)	12.0
Every huge change in production volume (N=25)	32.0
When improvement in technology is necessary (N=25)	40.0
Others (N=17)	35.3

Table 4.14 Frequency of design/redesign.

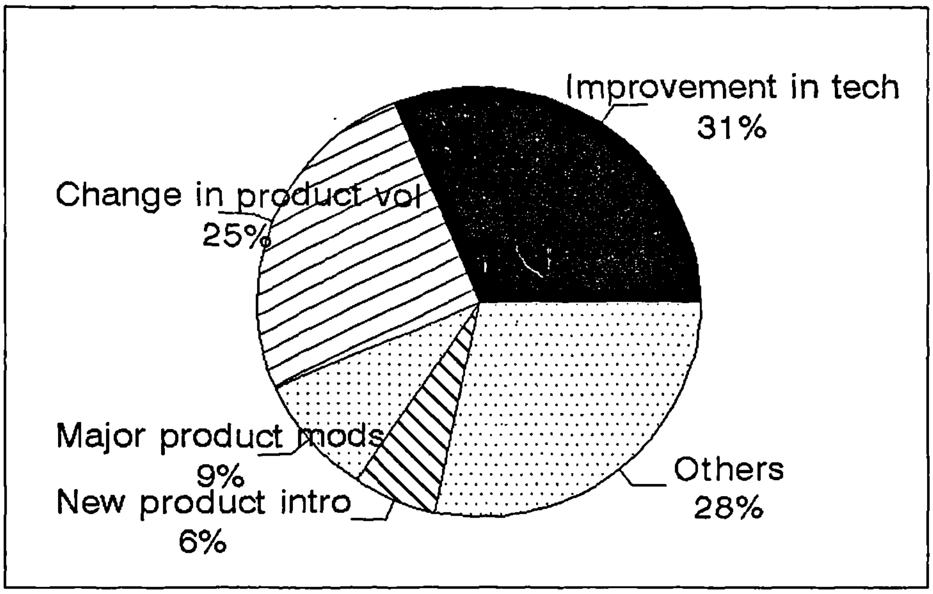


Figure 4.10 Frequency of design/redesign

A high percentage of the respondents (31%) indicated a single reason for initiating the design or redesign of their manufacturing systems as when there is the need to improve the technology of the system. Substantial number of respondents stated other reasons for undertaking manufacturing system design/redesign. These include: when competition dictates; on-going incremental development; evolution; continuous improvement to upgrade our subcontracting operation; and change in company policy, e.g. policy to adopt cellular manufacture.

4.3.4.7 Design Lead Time

Respondents were asked to indicate an estimate of the average lead time (man-month) i.e., the time required for the complete cycle of manufacturing system design. Obviously the actual times vary from a company set-up to another and from project to project. However, the assumption made in the survey was that the higher the investment, the bigger is the scale of the design project, which will be indicated by the lead time that is necessary to complete it. The results are shown in Figure 4.11.

Perhaps the more significant information with regard to reduced MSD lead time is the distribution of the lead time . This is shown in Table 4.15. Manufacturing system design is divided into four stages: requirements analysis, conceptual design, detailed design, and evaluation and selection.

Design stages	**Percentage of time spent (N=19)**			
	< 25%	25 - 50%	50 - 75%	> 75%
Requirements analysis	63.2	31.6	5.3	-
Conceptual design	86.7	13.3	-	-
Detailed design	15.8	63.2	15.8	5.3
Evaluation and selection	78.9	15.8	5.3	

Table 4.15 Distribution of design/redesign time.

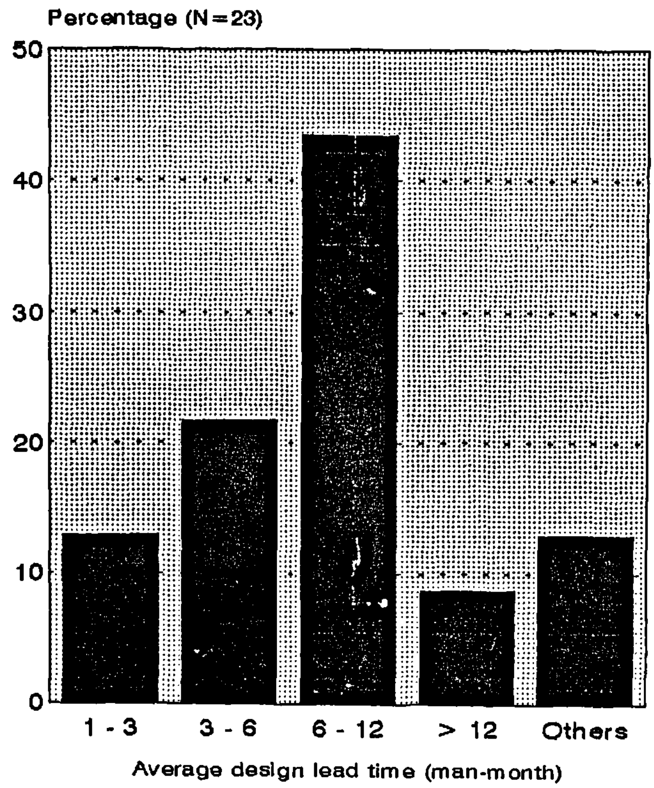


Figure 4.11 Average design lead time.

4.3.4.8 Departments Involved

Manufacturing system design is a complex activity and requires the involvement of multi-disciplinary team. The respondents were asked to indicate what departments were involved in the design of the manufacturing system in their organisation. This is shown in Table 4.16. Again the percentages are rationalised and shown in Figure 4.12.

	Percentage (N=27)
Manufacturing department	92.6
Industrial Engineering department	44.4
Product design department	33.3
Marketing department	18.5
Engineering department	55.5
Quality control department	66.7
Computer systems department	55.5
Equipment suppliers	29.6
Customer	22.2
Others: Logistics department (N=18)	16.7

Table 4.16 Departments involved in manufacturing system design/redesign (actual percentage of responses)

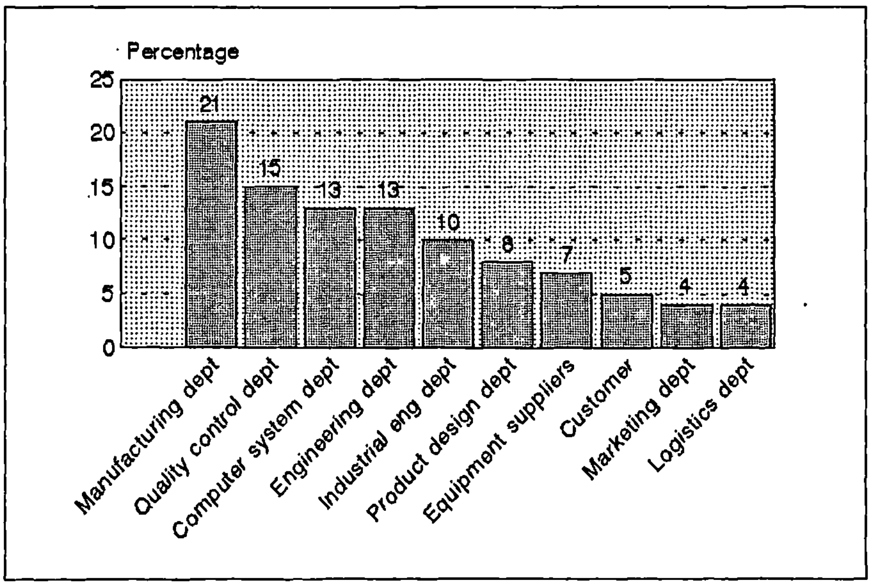


Figure 4.12 Departmental involvement in manufacturing system design (relative percentage)

4.3.4.9 The Role of Customer in Manufacturing System Design

Respondents were asked to indicate the significance of the customer in the process of manufacturing system design. Twenty six respondents provided the information. Table 4.17 shows that only one third of the respondents assigned high degree of significance on the role of customers.

	Frequency (N=26)
High significance	34.6
Some significance	26.9
No significance	38.5

Table 4.17 Significance of customer in manufacturing system design

4.3.5 Use of Design Methodologies and Tools

The questionnaire investigated the application of design methods and tools in three ways. Firstly in terms of the degree of awareness of the respondents, secondly in terms of the design stages in which they were used, and thirdly the extent to which they have affected the design process.

4.3.5.1 Degree of Awareness

The respondents were initially asked the extent to which they were aware of the various design methodologies and tools. There were three levels of awareness that had been considered. The first level was that the respondents were familiar with the methods and tools, and have used them in the company. The second level was whether the respondents were familiar but have not used any of them in the manufacturing system design. The last one was that the respondents were not familiar with them. The results are shown in Table 4.18.

The percentages in Table 4.18 verify that the overall level of awareness of the design methods and tools is relatively low. Respondents were more familiar with the more conventional approaches such as data flow diagram, input-output diagram, spreadsheet and group technology. Of the more non-conventional approaches, simultaneous engineering seems to be adopted by a substantial number of the respondents. A high degree of unfamiliarity is observed for the more non conventional methods such as SADT, IDEF, GRAI and artificial intelligence. This is summarised in Figure 4.13.

Methodologies/Tools	**Degree of awareness**		
	1	2	3
SADT	3.8	30.8	65.4
Data Flow Diagram	46.2	19.2	34.6
IDEF	7.7	3.8	88.5
GRAI Methodology	3.8	-	96.2
Input-output Diagram	34.6	26.9	38.5
Group Technology	38.5	50.0	11.5
Spreadsheet	69.2	30.8	-
Simultaneous Engineering	46.2	42.3	11.5
Graphical Simulation/modelling	34.6	26.9	38.5
Operational Research	26.9	19.2	53.8
Artificial Intelligence	7.7	7.7	84.6

Table 4.18 Familiarity with design methodologies and tools (1=familiar and use; 2=familiar but don't use; 3=not familiar) (N=26)

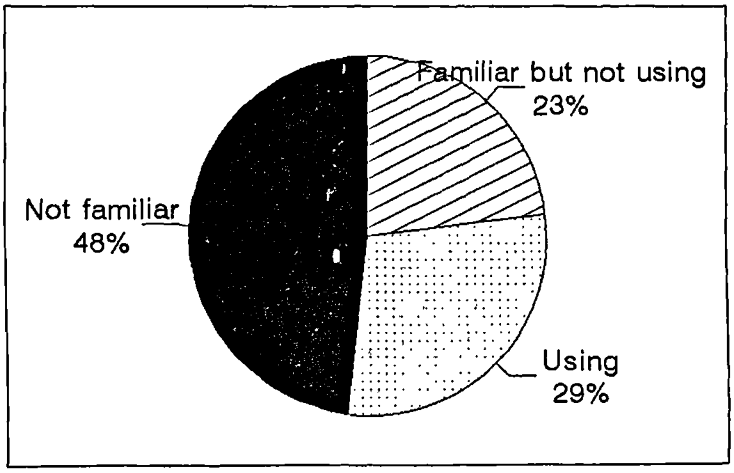


Figure 4.13 Summary of the level of awareness of design methods and tools

In order to obtain some indication of the usage of the methods and tools, each value of the percentage for respondents who were familiar and have used is divided by the sum of the percentages for the respondents who have used them. These normalised percentages are presented in the form of a bar chart in Figure 4.14. Each value of the percentage indicates the relative extent of application of each method in the whole spectrum of applications.

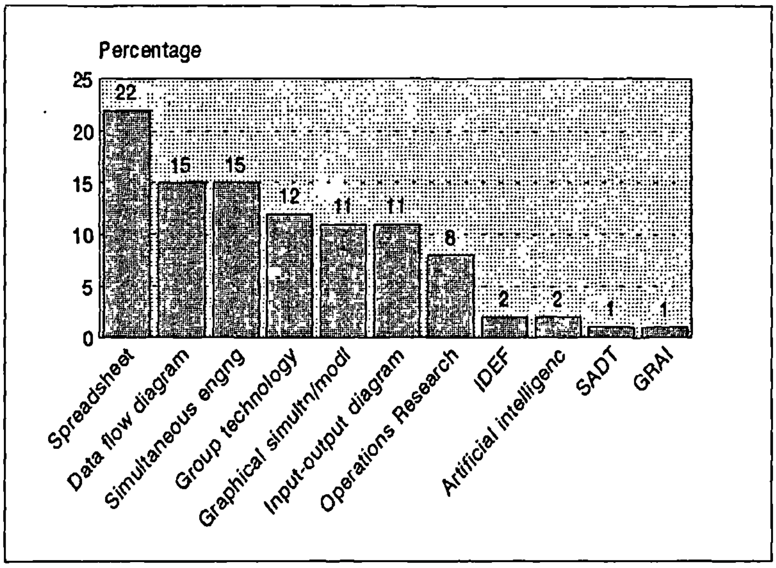


Figure 4.14 Relative usage of the methods and tools.

4.3.5.2 Stage of Application

In this instance, respondents were asked to indicate at what stages of manufacturing system design these methodologies/tools were used. The results are depicted in Table 4.19 and summarised in Figure 4.15. Figure 4.16 shows the application of the methods and tools in each of the design stage.

Methodologies/Tools	Application stage (N=26)			
	1	2	3	4
SADT	-	-	-	-
Data Flow Diagram	35.7	32.1	21.4	21.4
IDEF	3.6	-	-	-
GRAI Methodology	-	-	-	-
Input-output Diagram	26.9	26.9	15.4	19.3
Group Technology	26.9	19.2	15.4	19.2
Spreadsheet	53.8	34.6	23.1	46.2
Simultaneous Engineering	15.4	26.9	38.5	30.8
Graphical Simulation/modelling	15.4	23.1	19.2	15.4
Operational Research	3.8	11.5	7.7	7.7
Artificial Intelligence	-	-	-	-

Table 4.19 Application of design methodologies and tools (1 = use in requirements analysis; 2 = use in conceptual design; 3 = use in detailed design; 4 = use in technical evaluation and selection)

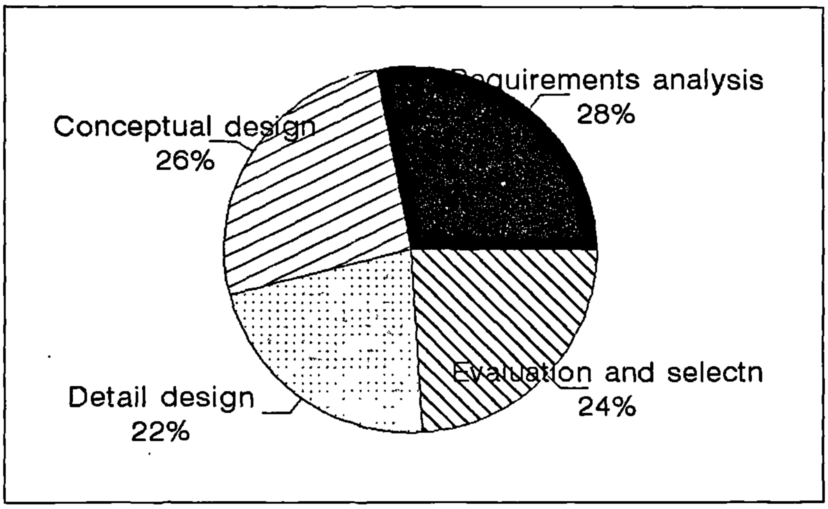


Figure 4.15 Distribution of the design stages in using the methods and tools.

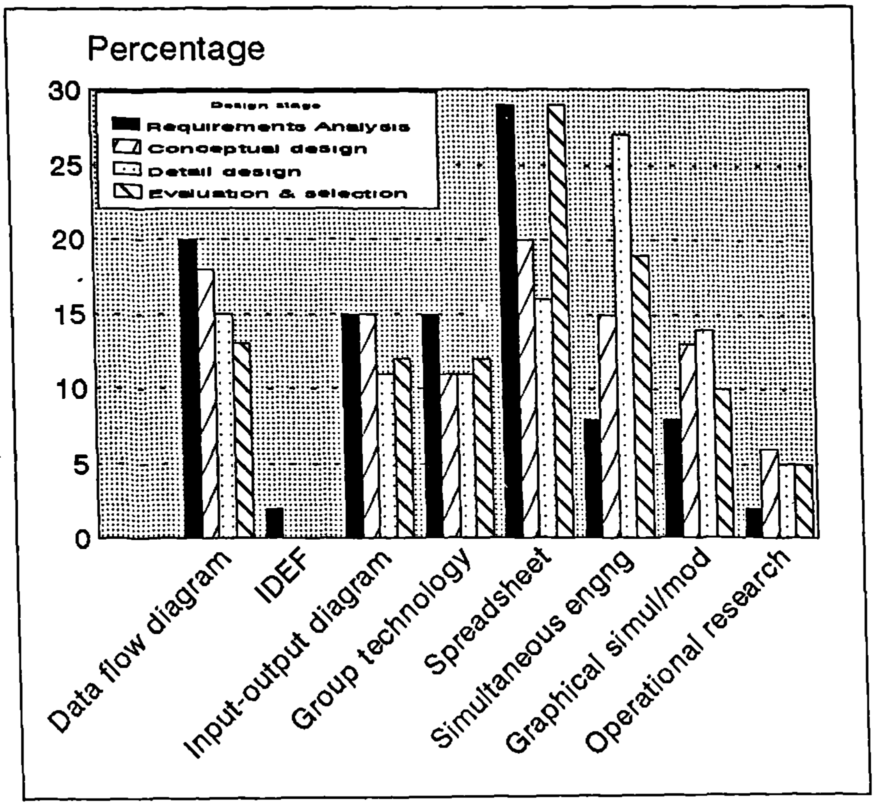


Figure 4.16 Application of the methods and tools in each of the design stage.

4.3.5.3 Degree of Effectiveness of the Methodologies/tools

Respondents were asked whether the methodologies/tools that they were using had any significant effect on the design/redesign process. This is to be indicated by stating whether the methodologies/tools: (1) Facilitate design process and improve design time; (2) Do not affect design process and design time; and (3) Worsen design process and lengthen design time.

As expected most respondents indicated that the methodologies/tools used have had positive impact in the design process. However some reservations were shown with regard to Group Technology, Spreadsheet and Simultaneous Engineering despite the more extensive use of these techniques. The highest degree of scepticism was expressed for operational research. The overall responses are shown in Table 4.20.

Methodologies and Tools	Effects on design applications		
	1	2	3
Data Flow Diagram (N=8)	100.0	-	-
Input-output diagram (N=8)	100.0	-	-
Group Technology (N=8)	87.5	12.5	-
Spreadsheet (N=16)	87.5	12.5	-
Simultaneous Engineering (N=11)	90.9	9.1	-
Graphical simulation/modelling (N=8)	100.0	-	-
Operational Research (N=4)	75.0	25.0	-

Table 4.20 Assessment of the effectiveness of the methodologies and tools (1 = Facilitate design process and improve design time; 2 = Did not affect design process and design time; 3 = Worsen design process and design time)

The data was further analysed in Figure 4.17 for relative effectiveness of the applications.

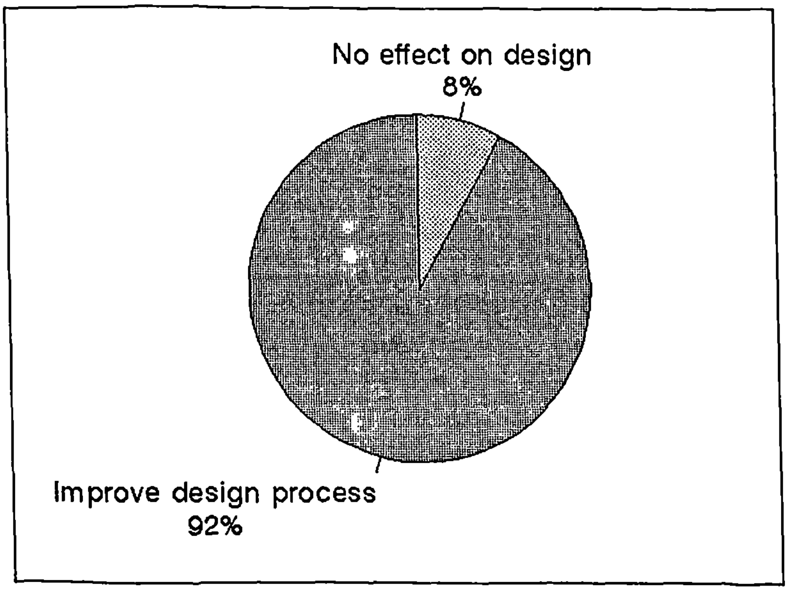


Figure 4.17 Effectiveness of using the design methods and tools

4.3.6 Major Constraints During Design

In order to put the design efforts and the application of methodologies and tools in perspective, the respondents were asked to state the major constraints during the design and development of the physical system of the advanced manufacturing system. The responses are shown in Table 4.21. The relative prominence of the various constraints is presented graphically in Figure 4.18.

Constraints	Frequency (N=27)
Objectives not clearly stated	55.6
Insufficient internal skill	48.1
Organisational and personnel related problems	40.7
Systems requirements poorly specified	25.9
Lack of planning and design tools	18.5
Lack of top management support	11.1
Others: Return on investment	10.0

Table 4.21 Major constraints during design/redesign.

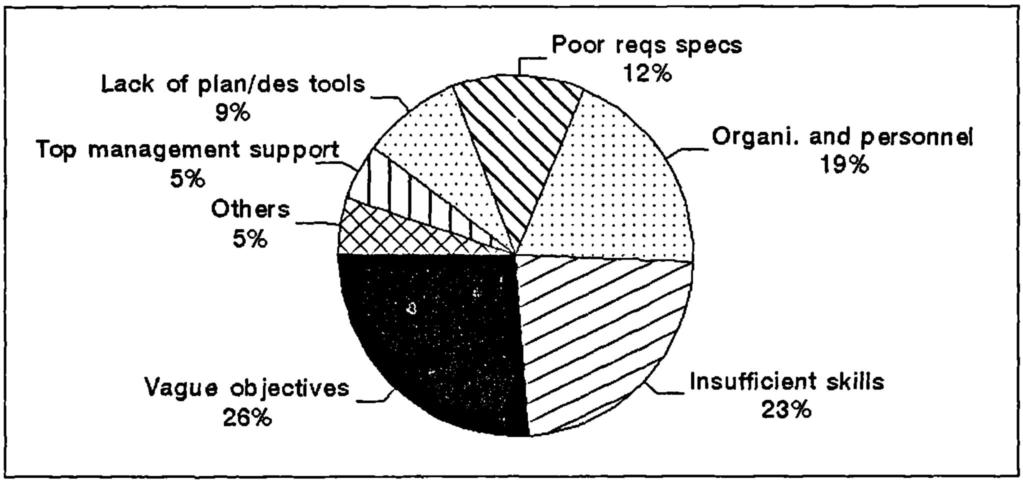


Figure 4.18 Relative percentages of the major constraints.

4.4 Discussions

In this section the results and the general trends that emerged from the survey will be discussed. Where comparisons or relationships between variables are to be made, they will be supported by outcomes from crosstabulations performed on the data using the SPSS/PC+. Otherwise tables and figures from Section 4.3 will be quoted.

4.4.1 General Background on Companies and Products

The survey has covered a broad spectrum of manufacturing companies. A total of 28 companies were included in the sample, giving a response rate of 11.2 percent. The replies were dominated by mechanical engineering companies (50%) and followed by companies involved in automotive parts manufacture. Companies under the categories of electrical and electronics engineering and instrument engineering made up 10.7% of the responses respectively. The majority of the responses received were from persons with the job titles of manufacturing or production managers (60%) while managing directors constitute 15% of the responses. The high percentage of participation by these management levels which were considered to be knowledgeable about their firms' environments and technologies, as well as having some responsibility for decision making in the process of manufacturing system design (MSD) provided some degree of confidence in the accuracy and reliability of the data.

In terms of the size of the surveyed companies, shown in Figures 4.1 and 4.2, 35% of them had the annual turnover of between £21-50 millions, while 21% had the turnover of more than £50 million. Four responses indicated the turnover of more than £100 millions. Only small number of the sample (less than 4%) had the turnover of less than £5 millions. Crosstabulation of the turnover and the number of employees indicates that of the companies that had the turnover of £21-50 millions, one company (12.5%) had between 101-200 employees, five companies (62.5%) had between 201-500 employees and two companies (25%) had more than 500 employees. The company with the turnover of between £51-100 millions had 201-500 employees. One had between 201-500 employees while three had more than 500 employees. The distribution of the size of the companies in terms of turnover confirms the initial assumption about the ability to invest in advanced manufacturing.

The number of part types produced in the manufacturing systems of the sample varied from less than 5 to more than 200 with the latter figure making up 56% of the responses, see Figure 4.3. The capability of the surveyed systems is indicated by the estimate of the production rate, which varied from less than one per hour (9%) to more than 100 per hour (14%). The majority of the sample (77%) had the minimum batch size of one, and 50% had the maximum batch size of more than 500.

In terms of the manufacturing activities performed, there is a fairly even distribution between machining, inspection and materials handling, as shown in Figure 4.5. Rotational machining has a higher percentage of application compared to prismatic machining. Apparently over 90% of the sample include assembly as their activities.

None of the companies in the sample manufactured to stock alone. Sixty percent of them manufactured to order alone, and 40% manufactured to both, stock and order. The figures for batch sizes and the type of manufacturing significantly affect the behaviour of the sample companies with respect to the requirements for flexibility and delivery, as discussed in Section 4.4.4.

4.4.2 Manufacturing System Development

On the question of manufacturing system development, only 60% of the respondents have developed their systems through the physical integration of the technologies. The remaining 40% have pursued integration through the implementation of manufacturing planning and control. Of the 60% of the companies that had developed the physical systems as shown in Figure 4.6, 42% developed their system from isolated CNC into flexible manufacturing cell. Twenty seven percent links their CNC machines with CAD and 8% developed from cell into the flexible manufacturing system (FMS). None of the respondents developed a full FMS from scratch. In order to evaluate the consistency of responses to the two questions, i.e., manufacturing system development and manufacturing system category, a crosstabulation was performed between the approach to manufacturing system development and manufacturing system category. It is found that 80% of the respondents who progressed from automatic and semi-automatic machines to CNC machines finally developed into manned flexible cells. Only 20% remained as job shop. For those who had developed by linking stand alone CNC to CAD systems, 60% proceeded to become manned flexible cells and 40% remained as job shop. These two developments explain the high percentage of manned flexible cell (56%) followed by job shop (22%).

Implementation of advanced manufacturing in a company is dependent upon its business position and current level of technology. A high capital investment is normally involved. Table 4.7 for example, shows that in more than 60% of the sample, the machine costs are more than 50% of the overall cost. The safe and financially attractive approach would be a step-by-step process whereby at each stage the system development can be justified in terms of its technological viability and financial credibility. This approach has been adopted by more than 75% of the respondents by virtue of developing their systems in-house.

4.4.3 Manufacturing System Performance

The success or failure of the investment in advanced manufacturing depends on ensuring economic returns in the short term and the effect of the project on the company's competitiveness in the long term. This can be measured along a few parameters which form operational objectives to be achieved, such as throughput time, work-in-progress, manufacturing cost, product quality, machine utilisation and flexibility improvement. Table 4.8 shows the actual responses with respect to the achievement of the performance measures. In Table 4.9 the performance measures are ranked by normalising all the percentages of the responses and summing them up for each of the measures. What Tables 4.8 and 4.9 signify is that although different companies may attach different degree of importance to each of the measures, there is not much difference in terms of the overall perception of the degree of achievement of the performance measures within the sample. Most of the respondents were satisfied with measures that concerned time (such as reduction in work-in-progress and increase in throughput time) and improvement in product quality. Despite this, machine utilisation appeared to be giving problems to most respondents as 42.3% judged it to be just average and only 11.5% thought that its performance had been very good. The negative correlation that existed between flexibility and machine utilisation is to be expected as to meet the flexibility demand, machines need to be stopped for part and machine set-up to accommodate the different parts. This will subsequently reduce machine utilisation.

One of the important consideration in MSD is whether the physical structure of the manufacturing system is congruent with the corporate mission of the company, as expressed through the manufacturing strategy. This relationship has been regarded as one of the central issues in the discussion of manufacturing strategy [219]. Based on a clear strategy the development of the right system will enhance the capability of the manufacturing operations. This relationship can be schematically represented as in Figure 4.19.

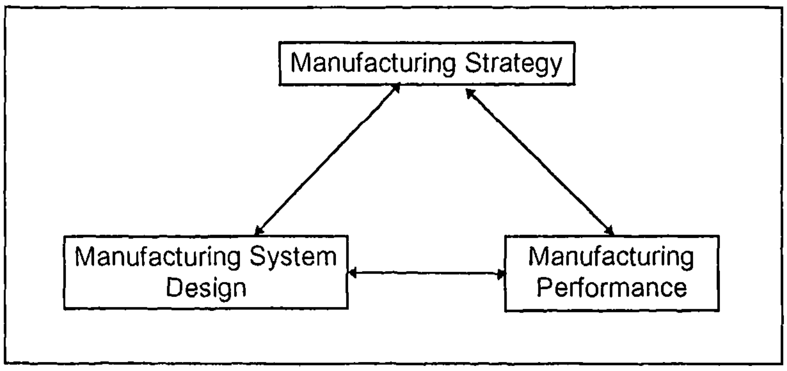


Figure 4.19 Relationship between manufacturing strategy, design and performance.

The relationships between the relative performance and the type of manufacturing system adopted is analysed and shown in Figure 4.20. The chart is constructed based on the percentage of respondents who considered the achievement of the various performance measures of their systems to be very good (scale of 5 in the questionnaire). Manned flexible manufacturing cell exhibited higher percentages of very good achievement for manufacturing lead time, throughput, work-in-process and product quality. In terms of manufacturing cost reduction and flexibility, both variables had the same percentage of responses for the manned cell and the flexible manufacturing system. Although the job shop has the highest degree of flexibility, it suffers great disadvantages in terms of the other performance measures.

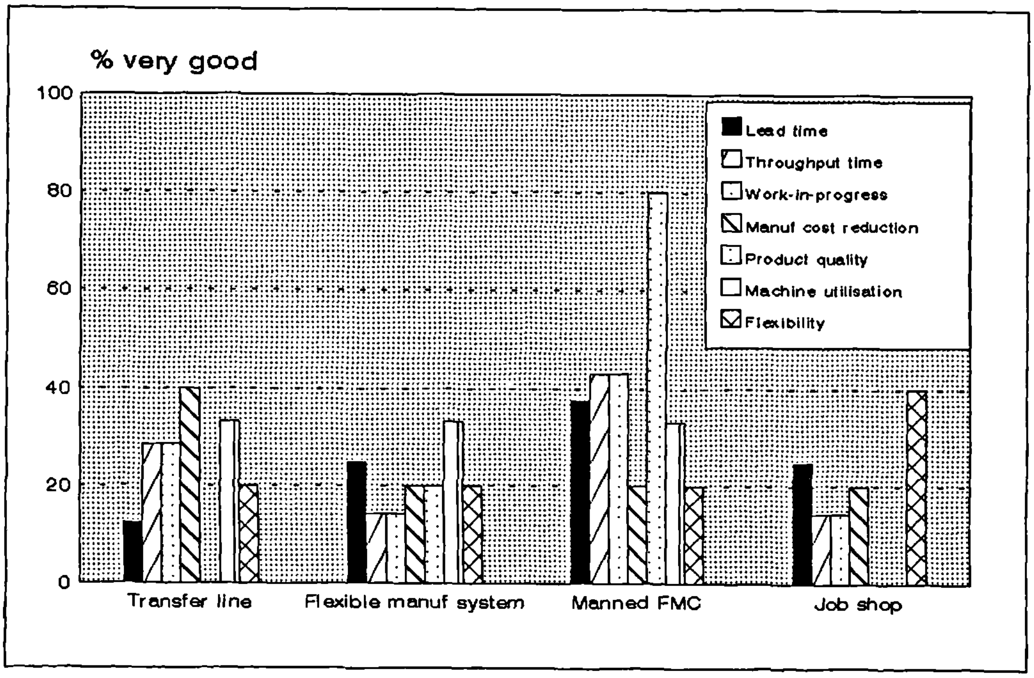


Figure 4.20 Perceived performance and manufacturing system adopted.

4.4.4 Manufacturing Strategy

Companies participating in the study displayed a high degree of importance to manufacturing strategy with 70% indicating having formal statement of manufacturing strategy. This is notable as it has been discussed in Chapter 2 that the existence of a manufacturing strategy will focus the resources of the manufacturing companies on objectives to be achieved (according to content model) and how to achieve them (process model). The significance of manufacturing strategy is evaluated by investigating the effects of its presence (or absence) on the achievement of the manufacturing performance. This is presented in Figure 4.21. The companies that indicated having a manufacturing strategy appeared to have attained better performance.

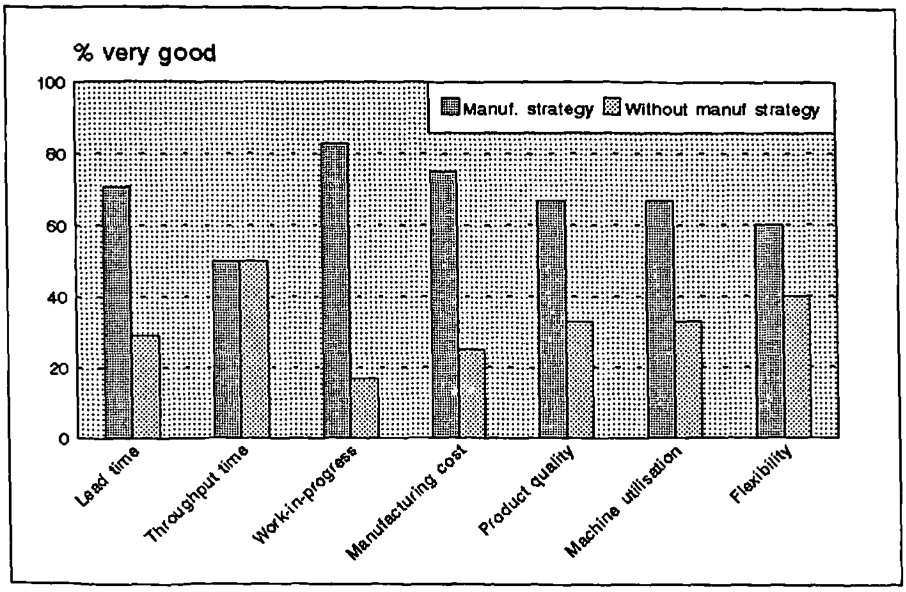


Figure 4.21 Influence of manufacturing strategy on perceived performance

Another interesting feature of the survey sample is that although 30% of the respondents admitted not having a manufacturing strategy, all responded to the question of competitive priorities or strategic objectives. This is indicative of the low degree awareness of the importance of having a well documented manufacturing strategy. Sandberg [227] argued that the lack of methods to support strategy formulation and validation will often create vague and weak strategies. This will result in decisions made and projects started without a thorough evaluation or definition of alternatives. New [191] further enhanced that 'a set of pious but incompatible hopes' such as 'deliver on the shortest lead time', 'always on time', 'a product with better features than those offered by the competition', 'to any design the customer wants', etc., are not a statement of manufacturing strategy.

Analysis of Tables 4.10 and 4.11 reveals that the majority of the respondents were comfortable with assigning, quality, delivery and cost as the most important strategic objectives to be achieved in that order. However flexibility occupy the lowest position in the ranking, with only 20% of the companies surveyed reported flexibility as the most important. The inference that can be made from this is that the majority of the manufacturing companies in the survey were more concerned with short term and easily quantifiable objectives, rather than the more strategic objective of flexibility. Nevertheless the results obtained in the survey appear to be in agreement with the general trend reported in the literature and summarised in Table 2.8.

Type of flexibility	Percentage of response	
	Present	Lim [1987]
Machine	21	20.0
Product	21	45
Volume	20	15.0
System	15	10
Process	10	10
Expansion	12	-

Table 4.22 Comparison of flexibilities.

The three most important types of flexibility pursued by the participating companies were machine flexibility (21%), product flexibility (21%), and volume flexibility (20%). Table 4.22 shows a comparison between the present study and the survey which had been carried out in another study [163]. There is a decrease of more than 50% in the importance of product flexibility between the two studies. This decrease can be explained by comparing the ability of the two samples to produce different part types. In the previous study [163], only 25% of the sample were able to manufacture more than 50 part types, whereas in the present survey, the figure has risen to 64%. Hence, the need for product flexibility has been met over the years. Another possibility is that product design has become relatively static, which placed more importance to the technology of manufacturing. This statement seems to tally with the figures for the major factors driving manufacturing system design, shown in Figure 4.10. New product introduction constitutes only 6% of the total reasons for design/redesign. The volume, system and expansion flexibilities also appear to have gained more prominence.

The use of flexible machines was the approach adopted by 69% of the respondents (Table 4.13), or relatively a quarter of the overall approach (Figure 4.8). Further significance of technological approach is evident from the high percentage of increasing tooling capacity and improving the machine control system. The use of multi-skill workers represents 42% of the respondents. Although claims have been made that cellular manufacturing provides a step-change increase in flexibility, only 30% of the sample has adopted the approach.

As indicated by Table 4.10, the highest number of companies in the sample attributed delivery as the most important strategic objective to be achieved. The positive correlation is also observed between companies that assigned delivery as the most important objective, with performance measures such as throughput time and manufacturing lead time reduction. Of the two aspects of delivery, reliability tend to be given considerably more importance compared to speed.

4.4.5 Manufacturing System Design Process

The need to design or redesign manufacturing systems are normally externally motivated, i.e., by the market. This could be in the form of the requirement of new product or improvement to existing products which need changes to the manufacturing systems. Additionally manufacturing systems could be redesigned to improve the performance of the current system. As shown in Figure 4.10, when respondents were asked how frequent the design process was undertaken, 31% stated that when improvement in technology is necessary, and 25% when there is a huge change in the production volume. It is notable that the percentage for major product modifications was higher than that for new product introduction. What can be deduced from the figures is that the system was originally designed to cover a wide spectrum of products. As mentioned before 56% of the systems surveyed were able to manufacture more than 200 part types. The higher percentage for product modifications were due to the redesign of modification to the system. Other reasons that had been cited appeared to be quite vague. These include statements such as when competition dictates, evolution and change in company policy. Another conclusion that can be drawn based on the evidence of low percentage of response for new product introduction as a trigger for manufacturing system design, and the observation in Table 4.20, is that the level of new product introduction in the manufacturing industry in the UK for the past ten years has been low as a whole.

In terms of the actual time taken for the design/redesign process, 44% of the responding companies stated 6-12 months. About 9% took more than a year to complete the design and implementation process. The breakdown of the design lead time is shown in Table 4.15. It is apparent from the table that less time was spent on requirements analysis compared to detailed design. This is contrary to what has been proposed in most literature. Allocating more time to the initial requirements analysis and conceptual design will ensure that the system design and implementation can fulfil the operational objectives as well as the long term strategic objectives.

The manufacturing system design is seen as a highly technical task by the respondents by virtue of the higher percentages given to the technical departments. What is significant from Table 4.16 and Figure 4.12 is that the lower percentage of involvement by the marketing department (4%) and customer (5%). The attitude of the surveyed companies towards customer was also notable. Despite only 5% of the sample recognised the significant involvement of the customer in MSD, nearly 60% thought that customers do have a certain degree of significance. In order to verify this initial observation, a crosstabulation was performed between the degree of significance of the customer and the perceived performance, Figure 4.22. The chart shows that in most measures of performance, the perceived achievement had been very good where the companies considered the role of customer as significant.

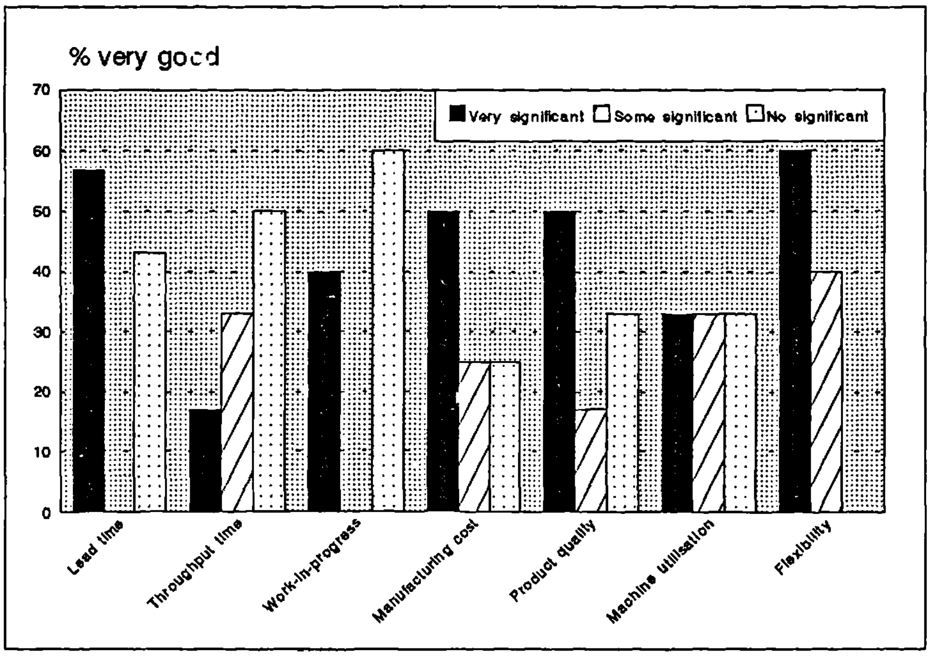


Figure 4.22 Influence of customer.

4.4.6 The Use of Design Methodologies and Tools

Manufacturing system design is conceptualised as the mapping of the performance requirements of a manufacturing system onto suitable values of decision variables, which describe the physical design or the manner of operation of the manufacturing system. The problems associated with the design process are numerous and complex, and they have been elaborated in Chapter 2. In addition to these problems companies are also faced with the challenge to remain competitive. Competitiveness is characterised by the shortening of product life cycles and the rapid advances of technologies. The implication to MSD is that the design should be flexible to accommodate changes in demand over a longer time period, and the system design process should be effective and take a shorter lead time.

Design methodologies and computer tools have been developed to support MSD process. Detail review was given in Chapter 2. The important questions related to the design methodologies and tools involve the extent of application in industry and the degree of their effectiveness. Table 4.18 contains the responses to the question of the level of awareness of the respondents of the methods and tools. These are summarised in Figure 4.13. Nearly half of the surveyed companies were not familiar with some of the techniques listed. In the event, 23% were familiar with the techniques but were not using them, and 29% were using them to a certain extent. This finding tends to support one of the key results of a study by Fritz et al., [88] that the UK companies are lagging behind the German companies in the use and development of advanced computer tools and integrated systems for the purpose of MSD.

The relative percentage of application of the various techniques are shown in Figure 4.14. The use of spreadsheet as a design support predominates the rest. One possible reason for this is the extensive availability of packages in the public domain and the relatively ease of use for data handling. Although both data flow diagram (DFD) and structured analysis and design technique (SADT) originated from applications in the design of computer systems and programming, DFD (15%) was more extensively used than the SADT. This could be due to the wider dissemination on the application of DFD as part of Structured System Analysis and Design Method (SSADM) which has been adopted as a standard UK government approach to designing information systems.

Simultaneous engineering approach has been adopted to a certain extent (15%). This is not surprising as the emphasis on time to market as a competitive weapon means that companies are using it together with product design. Group technology, simulation, input-output diagram and operational research occupied the middle region with relative application of between 8-12%. Techniques that had the lowest degree of application were IDEF, artificial intelligence, SADT and GRAI method. Although IDEF and GRAI methods enjoy a reasonable coverage in the academic literature, it appears that in general most of the respondents were not familiar with the methodologies.

In order not to create ambiguity in terms of applications, quality function deployment was not included in the list. However a space was provided in the questionnaire for the respondents to include if QFD was ever used. From the returned questionnaires, there was no evidence to suggest that it was used in manufacturing system design/redesign.

With regard to the stage of design in which the methods and tools were used, there was no significant difference in the distribution of applications, as shown in Figure 4.15. The requirements analysis however, utilised a slightly higher percentage of the methods. Analysis on the frequency of application of the individual technique during design is presented in Figure 4.16. Most application of spreadsheet was in the requirements analysis and, evaluation and selection phases. Simultaneous engineering tend to be used more during detail design. For graphical simulation and modelling, its application was greater in conceptual and detailed designs.

The primary aim of the development of the design method and tools was to improve support for MSD so as to reduce design lead time, increase the quality of designs and enhance the overall design effectiveness. The responses from the participating companies indicated an overwhelming agreement that the application of these methods and tools did have positive effects on MSD tasks, as shown in Figure 4.17.

4.4.7 Major Constraints During Design

Figure 4.18 shows the types of problems that the respondents faced during manufacturing system design. The absence of clear objectives appeared to be the main factor that can reduce the effectiveness of MSD. This is followed by insufficient internal skills and the organisational and personnel related problems. Poor requirements specifications constitute 12% of the overall constraints. Only 9% of the overall constraints were due to lack of planning and design tools. Hence it can reasonably be deduced that the major problem faced by the sample was organisational, rather than technical. This finding on socio-technical aspect of manufacturing system design is in agreement with that of Larsson and Sandberg [157].

4.5 Summary

The implementation of the appropriate form of manufacturing system will enhance the competitiveness of manufacturing companies. There are a number of configurations of manufacturing systems that are technically feasible, and are defined by parameters such as product range, machining systems, storage facilities, material handling systems and expansion opportunities. In terms of the development of manufacturing systems, the survey has shown the popularity of manned flexible manufacturing cell as an approach to improve performance and fulfilling the objectives of manufacturing strategy.

The need to have a clear manufacturing strategy is recognised by the majority of the participating companies. There is also evidence from the survey that suggests the relationship between manufacturing strategy and manufacturing performance. The respondents who indicated having the manufacturing strategy appeared to have better performance than those who did not have. The order of priority of the competitive advantages of the sample is found to be as follows: quality, delivery, cost and flexibility.

Improvement in the technology and change in product volume were the two predominant reasons for the surveyed companies to undertake manufacturing system design or redesign. New product introduction appeared to be the least significant reason for engaging in manufacturing system design. This finding is supported by evidence of the decrease in the importance of product flexibility requirements of the manufacturing systems.

It appears from the industry response received that the level of application of manufacturing system design methods and tools is shown to be relatively low, i.e., only 30% of the sample. For those companies that used any of the methods, the percentage of applications for the more common tools such as spreadsheet was higher compared to other tools such as IDEF, SADT and AI. In general the use of manufacturing system design methodologies and tools has the tendency to improve the effectiveness of the design process.

CHAPTER 5

THE FRAMEWORK OF DEFINING MANUFACTURING SYSTEMS DESIGN REQUIREMENTS

5.1 Introduction

This chapter describes the development of the framework for the hierarchical decomposition of the requirements for manufacturing system design. The development of the framework is based on the concept of macro planning whereby the objective is to fulfil the strategic objectives of manufacturing system by explicitly addressing the external requirements expressed in terms of the voice of the customer or the market. The fundamental or strategic requirements of price, quality, delivery and flexibility are decomposed into a hierarchy of systems functions which consist of five separate levels. The hierarchical approach of system design provides a structured method of identifying the complex relationships that exist among the requirements at various levels and subsystems. The analysis of requirements is limited to the technical issues.

By using the planning matrices of quality function deployment, these design requirements are deployed down the hierarchy to the most basic elements that make up the physical system configuration. The significant feature of connectedness of the Quality Function Deployment (QFD) conceptual framework is fully utilised to demonstrate the impact of the decisions taken at the lower levels of the hierarchy on the achievement of the firm's business objectives. The discussion is preceded by the reiteration of the importance of up-front or macro-planning. Based on the relationship between the criteria of manufacturing system design and the conceptual framework of quality function deployment, the case is argued for the suitability and viability of the proposed methodology. This is then followed by detailed description of the requirements.

5.2 The Significance of Up-front Planning

The manufacturing system design function is primarily responsible for the provision of resources for the operations function. The optimum configuration of the technological resources within a manufacturing system will ensure the attainment of business objectives of the firm. This in turn depends on the up-front planning which includes detailed specifications and comprehensive needs analysis of the system to be built. The concept of *macro planning* [49, 106, 192] or manufacturing system design problem Type 1 [202], as the first step in an iterative process of designing the manufacturing systems has a significant role in facilitating the whole design and implementation project. A clear specification of what requirements that need to be fulfilled will ensure the right type and amount of resources are allocated. This optimising effort is essential as the design and planning tasks of manufacturing systems are becoming increasingly complex in terms of the number, diversity, and mix of system components.

The task of macro planning is characterised by the development of the answers to the question, "How should a factory look and operate if it is to produce the products at the expected mix and volume in a way that is consistent with the business objectives?" The question reflects the major issues that need to be addressed in design which are strategic in nature. They involve decisions on the quantum of resources to be provided, their capabilities, and decisions on operating policies. These broadly constitute system specifications [145], and serve as input for decisions regarding the selection of system hardware and software components. This initial overall planning in any manufacturing system is the most important stage, to the extent that if the systems analysis is not conducted properly the final system proposal stands a high chance of being inadequate [103].

5.3 The Criteria for the Design and Specification Methodology

The process of specifying and designing a manufacturing system starts with a set of given requirements and ends when the system is described in sufficient details that it can be implemented. At this stage a distinction is made between the terms used to describe a methodology, a technique and a tool. A methodology is a set of methods, rules and postulates utilised by a discipline. In any particular situation the methodology should be able to guide the designer towards a method uniquely suitable to that particular situation [44]. A tool is something (as an instrument or apparatus) used in performing an operation. As an example, $IDEF_0$ is a tool used in the structured methodology. A technique is the manner in which technical details are treated.

The task of specification and design is to take designers through the process of formalising the requirements and transforming them into constructs that can be implemented. These requirements which are normally external and expressed in non-technical terms need to be translated into suitable engineering or technical requirements. In order to be effective in achieving the specified objectives, and valid for a wide range of applications a manufacturing system design methodology should have certain generic characteristics that would make the methodology robust in various situations and circumstances. Two important issues that need to be considered are firstly, whether the system developed fulfils the requirements which were initially set out in the objectives, and secondly whether the system generates a return sufficient to justify the investment. These two issues are further elaborated in terms of other characteristics. Based on a review of the requirements that a system design methodology should have, the following is a summary of the characteristics which have been identified [124, 173, 295]:

- Systems perspective, i.e., it is critically important to view the objectives of the organisation, its resources, and the various elements within the company from systems perspective. The design methodology must also be systematic in its approach. The systems approach of the methodology must be able to describe the system under three different, but closely related views: functional, structural and behavioural.

- The methodology must address the strategic issues of manufacturing system design. It is also essential to ensure the existence of a core theme which sets the agenda for change.
- The methodology must specify appropriate tools, techniques and approaches. A tool is a mechanism to allow the generation and clarification of ideas and thoughts.
- It should be easy to understand and use by designers.
- The methodology should provide quality specification. A good specification will facilitate the translation of design objectives into a system design which can be implemented in practice without major difficulty.
- An efficient methodology will reduce systems design costs and cycle times. Due to scarce resources required for the design process, a design methodology can help alleviate this problem by providing guidance for the design process and routinising parts of the process.
- Fitness for purpose. The methodology should offer means of assessing whether the correct decisions are being made during the design process.
- A good design methodology should minimise the cyclical or iterative steps in obtaining optimum designs, but rather, should deal with all aspects of the system concurrently.

From the above descriptions it can be deduced that there are three factors that are more important than others that need to be considered in the design framework of the manufacturing systems. These are the systems approach, the strategic framework of the methodology and the existence of appropriate tools and techniques for design implementation.

5.3.1 Systems approach

The adoption of the systems approach in manufacturing systems design is necessary because an engineering manufacturing business is an integrated whole composed of parts or subsystems linked to achieve a set of common goals. The systems perspective of manufacturing stresses the interdependencies that occur among the individual elements and activities within the system. The characteristic of the systemic approach to design [44], i.e., 'the whole is greater than the sum of its parts' underlies the importance of the overall optimisation, rather than individual or local optimisation. In addition, the design process is approached in a systematic manner.

5.3.2 Strategic Framework

The main aspect of the strategic framework is that all tactical and operational functions or tasks should contribute to achieving the strategic or competitive advantages of the firm. This is essential in order to prevent decision making based on short term thinking. For example, a system that exhibits low initial investment cost may not result in the long term flexibility or quality benefits. In addition, the methodology of manufacturing system design must have a mechanism to ensure that only specialised technical problems which are essential to the needs of the overall business objectives are addressed. This will avoid the firm from spending unnecessary resources.

As discussed in Chapter 2, the need to address the strategic objectives in the design and implementation of manufacturing systems has been stated either explicitly or implicitly in some of the design methodologies that have been reviewed. However, the manner in which this could be achieved has not been shown clearly.

5.3.3 Tools and Techniques

The process of system design to create a system capable of fulfilling design objectives is normally a structured problem. Hence in any design methodology there must exist some form of logical procedures to translate ideas and design objectives into a complete design. Such procedures utilise design tools and techniques that will provide the mechanism for the generation and clarification of thoughts or ideas. In addition they also facilitate the presentation of data and information, hence aiding the decision making process. Such a tool or technique could be a diagram, a table of figures, a mathematical procedure or a particular modelling technique.

5.4 Objective

The objective of the methodology to be developed in the present work is to adapt the approach of Quality Function Deployment (QFD) in the definition and specification of a class of advanced manufacturing system. As mentioned in Chapter 3, the QFD approach has been developed as an advanced quality system made up of an integrated set of quality tools and techniques to provide customer-driven products and services. The focus of QFD has been shown to be in two principal aspects:

1. *What* is required to satisfy the customer (the customer requirements), and
2. *How* important are things to the customer (the relative importance).

QFD applies its tools and techniques to improving the *product*, and to the *process* of product development (and services). The procedures inherent in the approach allows trade-offs to be made on parameters that affect the objective of meeting the customer requirements.

It has been shown in Section 2.5 that there are strong and important relationships that occur between manufacturing strategy and decisions on technological investment. However, it has also been shown that there appears to be limitations with regard to *how* these two entities are connected. Hence in this work, QFD principles will be used in developing forward strategies (systems functions) into the design of the physical subsystem of the manufacturing system. The methodology will enhance the strategic links that exist between the business objectives and the decisions on technologies. The conceptual model of this new methodology is shown schematically in Figure 5.1.

The methodology will utilise the tools within the QFD approach in order to facilitate the translation of strategic objectives of the manufacturing firms to the tactical and operational decisions of the manufacturing system design. This is to be achieved through two main stages :

1. The requirements to be deployed will be decomposed into various details assigned to different levels of a manufacturing system requirements hierarchy, and

2. The planning matrices (or Houses of Quality) of the QFD approach will be utilised to deploy the requirements.

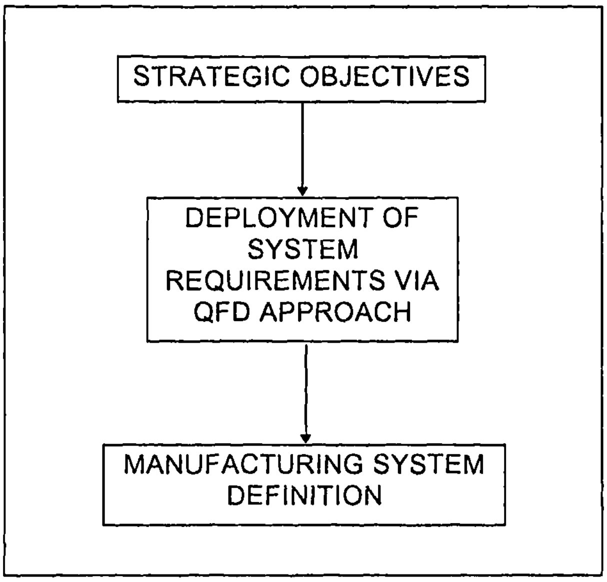


Figure 5.1 Conceptual model of the new design methodology.

The proposed methodology is thus an attempt to apply the QFD approach to the specification of a manufacturing system based on a set of the most fundamental criteria that a manufacturing enterprise needs to fulfil in order to stay competitive in the dynamic manufacturing environment. Starting from the combination of competitive advantages that the company adopts, these requirements which represent the dimensions of the manufacturing strategy, will be deployed in stages using the planning matrices. The final outcome will be the specification of the technologies that are required in order to fulfil the requirements of the various elements of the manufacturing system.

5.5 The Suitability of the QFD Approach in Manufacturing System Design

The initial assumption to be made is that it is possible to use the QFD approach in manufacturing system design. This is based on the observation of the trends in QFD usage in a number of applications other than product design. However the question to be answered in moving from product planning and design to manufacturing system planning and design is to what extent it is suitable. It is anticipated that some adjustments and modifications to the original QFD approach need to be undertaken. These modifications are necessary as a result of two major differences that exist between the nature of problems and decisions involved in the two situations:

- In the case of manufacturing system, the aim is to deploy the system functions (which include the quality function). This is represented by a set of the most fundamental requirements, expressed in terms of the competitive advantages of the manufacturing strategy, that the system needs to satisfy in order to fulfil the strategic requirements and hence to achieve business objectives as a whole. In the original QFD application for product design what is deployed or translated is a set of quality functions based on customer requirements. These are normally expressed more explicitly and refer to a single or a particular group of products.

- In manufacturing system planing and design, the system designers do not deal directly with the customer, i.e., the requirements of the customer and the influence of the competitive environment are expressed through the intermediate requirements on the products as well as the enterprise or production systems. This relationship is shown in Figure 5.2. The 'customer' in this case is highly internally oriented. There two types of issues which could be addressed with respect to products. Firstly, it could be the requirement to meet a spectrum of different products at a particular moment in time. Secondly the scope of design could be looking at a particular product over a period of time.

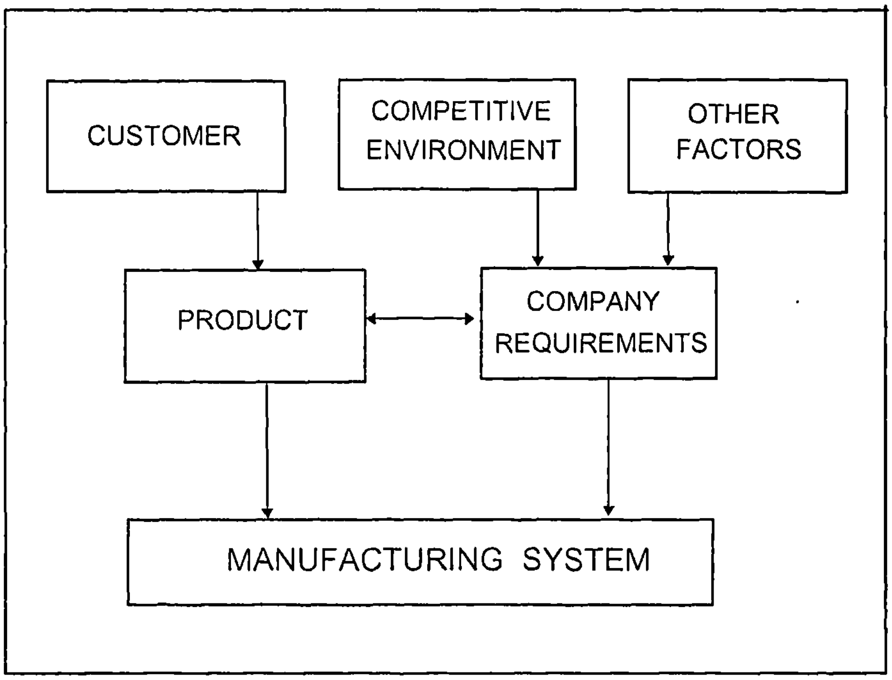


Figure 5.2 The requirements driving the design and development of manufacturing systems.

In order to assess the suitability of the QFD approach for manufacturing system design, a comparison is made between the set of criteria for design methodology of manufacturing systems based upon an examination of current research trends and the elements of the QFD conceptual framework. This is shown in Table 5.1. The relationships that exist between the elements in each group indicate that there is a high degree of congruency between manufacturing system design criteria and the conceptual framework of the QFD. The systems approach encompasses both the systematic procedure as well as the systemic nature of the design process. This is matched by the philosophy of moving the requirements upstream which ensures a wider scope of problem analysis is covered. This philosophy will also provide the opportunity for system designers to utilise strategic framework as a basis of other decisions. The strategic framework is further enhanced by the customer satisfaction mindset, which focus the design efforts on specific goals. The explicit connection between the decision making in QFD, as depicted by the planning matrices makes the whole sequence of processes easy to understand and use. Furthermore the use of planning matrices enable a broader system design issues to be tackled concurrently, thus reducing the iterative process of design. The involvement of interdisciplinary teams in QFD implementation improves communication and facilitates problem solving as the problems and solutions are viewed from different perspectives, thus fulfilling the systemic aspect of the design process.

QFD concepts	Criteria for MSD
Moving upstream philosophy	Systems approach
Customer satisfaction mindset	Strategic framework
The use of tools and techniques	The use of tools and techniques
Connectedness of decision making	Easy to understand and use
People and teamwork	Concurrent approach

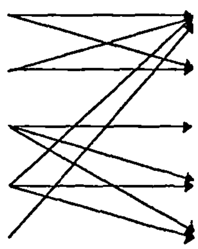


Table 5.1 Comparison of the QFD concepts and manufacturing system design criteria.

5.6 Manufacturing System Model

A model of the real system is a representation of that system in another medium, usually in a simplified form. In general, models are used to describe how a system works and behaves. The primary uses of models include optimisation, performance prediction, control, insight, and justification. In the present work the role of the manufacturing system model is to provide better understanding or insight into the decision making process in the manufacturing system design. A model of the domain of manufacturing system is required so that the framework of the analysis can be appropriately defined. In order to facilitate the study of a complex entity such as manufacturing system, a simple and intuitive model needs to be developed such that subsystem elements and the relationships among the elements can be described.

Three approaches are commonly used to model a manufacturing system [158, 273]. These are hierarchy, process-based and task-based. Hierarchy is the most conventional method, where a factory is decomposed into departments, lines, cells, machines and operations. This is a centralised method with the advantages for top-level planning and control. Within the hierarchical structure, the system at one level can be a sub-system or even a component of higher system. The second method is process-based model which deals with the flow of materials and components. Such models are suitable for handling the scheduling and performance improvements problems. Quantitative measures such as time and volume are the typical features of such models. The third type is task-based models which view manufacturing as a series of distinct tasks; e.g., design, fabrication, assembly, test and maintenance. These models are appropriate for the study of organisational infrastructure. The use of QFD for product design and development is implicitly based on this model. The satisfaction of the overall quality is subject to the quality function being deployed within each of the tasks.

The proposed methodology utilises both the hierarchy and task-based concepts of modelling in addressing the manufacturing system design requirements. The hierarchical perspective of the requirements illustrate their vertical interaction. The classification of the requirements into respective tasks provide the lateral interaction and indicates the multicriteria nature of the design problem. In addition the distinction of requirements into different tasks or functions provide the necessary view points in the deployment process.

5.6.1 Hierarchical Model of Manufacturing System

Hierarchies arise naturally in the design of complex engineering systems such as the manufacturing system. Such system is composed of linked elements, from relatively large and complex subsystems to stand-alone individual components. The principle has been used in models that describe the static representation of the system [12, 76, 267]. The hierarchical approach has been shown to facilitate the analysis of the planning and control problems of manufacturing systems [40, 48, 217]. The nature of the hierarchical approach in this case is that the management and control of the management system is divided into a hierarchy consisting of a number of associated levels or layers. Information flows only between adjacent layers. Each level is characterised by the length of the planning horizon and the data required for the decision making process.

The hierarchical model of manufacturing system to be used in the present work is shown in Figure 5.3. In this type of model a manufacturing enterprise (or production system) is decomposed into manufacturing systems (departments or areas), cells, machines and processes. This decomposition provides flexibility when manufacturing systems of different size and complexity are analysed. For larger manufacturing organisations with a number of manufacturing systems operating, the model allows focus on any particular system to be considered. For smaller companies, the production system and manufacturing system could be one and the same. The model is still valid.

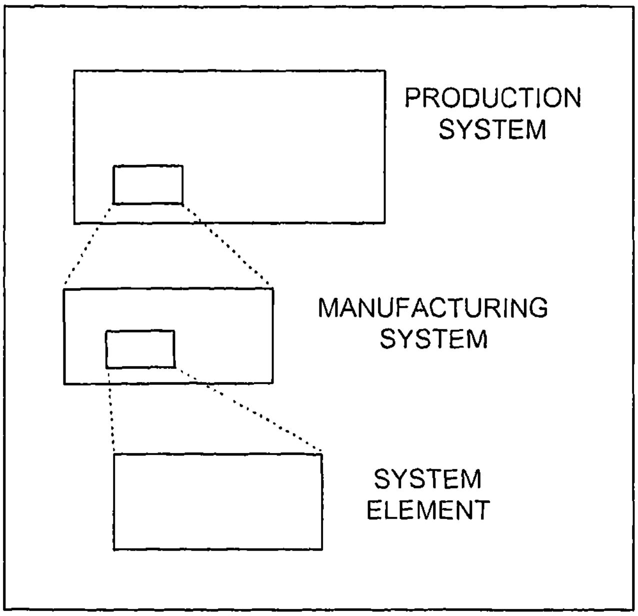


Figure 5.3 Manufacturing systems hierarchy.

5.6.1.1 Production System

A production system refers to the entire facility or enterprise and it includes the manufacturing system. It is assumed to be the highest-ranking term in the manufacturing hierarchy. From the understanding of the open system concept discussed in Chapter 2, a typical production system is a complex organisation that consists of all the functional areas such as marketing and sales, design and engineering, purchasing, manufacturing, production planning and control, quality control and distribution. In addition it also interacts with a wide range of external factors (environment) such as the customer, suppliers and vendors.. The main objective of the production system would be to fulfil the requirements of the competitive market through the interactions of its tasks and functions

5.6.1.2 Manufacturing System

A manufacturing system is a complex arrangement of physical elements which interact to produce outputs characterised by measurable parameters. The physical elements are machines, tools, workholders, material handling equipment and people. The task performed include material planning and production, which are collectively called operations. The measurable parameters include throughput time, production rate, WIP inventory, percentage defective, percentage on-time delivery, and total cost or unit cost.

This definition is preferred to other definitions such as 'manufacturing system is formed by the combination of manufacturing processes', as the above definition reflects the physical composition of the manufacturing system. The complex arrangement is the design of the manufacturing system. The design activity itself is a complex process involving decisions on the structure, operation and control of the system, as discussed in Chapter 2. It is responsible for the provision of resources for the operations function. Different system will result in different types and levels of measurable parameters. The manufacturing system co-operates with other functions such as product design and marketing in order to achieve the business objective of the enterprise or company.

In the context of the present work, the complexity of the manufacturing system can vary from a flexible manufacturing cell consisting of two to six processing equipment, to the full scale flexible manufacturing system consisting of several cells. This variation is necessary so that the methodology can be adopted by a wider spectrum of manufacturers, depending on the level of investment and the magnitude of the required system.

5.6.1.3 Manufacturing System Elements

These are the individual subsystem occurring at the lowest level of the manufacturing hierarchy, whose functions are integrated to achieve an effective manufacturing system. They can be a group of equipment, such as machine tools, or a subsystem such material handling equipment, controller or robots, or a group of quality tools or practices. Through customisation and the use of standards, these equipment are physically integrated within the manufacturing environment. Each of the entity has inherent properties which may create constraints on the system layout and integration. The problem of integration, although highly acknowledged, in not within the scope of the present work.

The hierarchical representation of the links and relationships between the elements within the manufacturing system and production system involves an ordered and directed set of decisions with a single parent or dominant decision located at the production system or enterprise level. In addition, as the levels of the hierarchy are propagated from top to bottom, the nature of decisions shifted from strategic to more tactical.

5.7 The Theoretical Aspect of Hierarchy

Since hierarchical approach is used in both the analysis of manufacturing systems and the development of the methodology, it is imperative that the theoretical aspects of hierarchy is briefly reviewed.

5.7.1 The Nature of Hierarchy

As previously mentioned, a complex system such as a manufacturing system can be perceived as being composed of various entities with interacting relations. A hierarchy formalism of the system emphasises the arrangement of entities in hierarchies or on the hierarchical relationships between entities. Conceptually, a hierarchy is a particular type of system in which entities (or elements) can be grouped into disjoint sets (or levels), with the entities of one group influencing the entities of only one other group and being influenced by the entities of only one other group [224]. A *hierarchic system* has been defined as a system composed of interrelated subsystems or entities, each of the latter being, in turn, hierarchic in structure until some lowest elementary subsystem is reached [238]. The entities in one level represent the most fundamental factors in achieving the objective of the next higher level in the hierarchy. They are independent of each other and each entity contributes to the whole system by performing its own function.

5.7.2 Conjunctive and Disjunctive Hierarchy

Based on their work on concurrent engineering systems, O'Grady et al. [194], propose three types of hierarchy using the criteria of how general concepts and details are distinguished, that is on how lower and higher-level nodes are inter-related as shown in Figure 5.4. A node is meant to be the point where an entity is decomposed. In *conjunctive hierarchy* a node in a level is desegregated into several subnodes, with each subnode representing a proper subset of its parent node activities in more detail manner. *Disjunctive hierarchy* describes a situation where distinct subnodes showing a common parent node represent alternative methods of satisfying the parent node. A *hybrid hierarchy* uses themes from both conjunctive and disjunctive hierarchies.

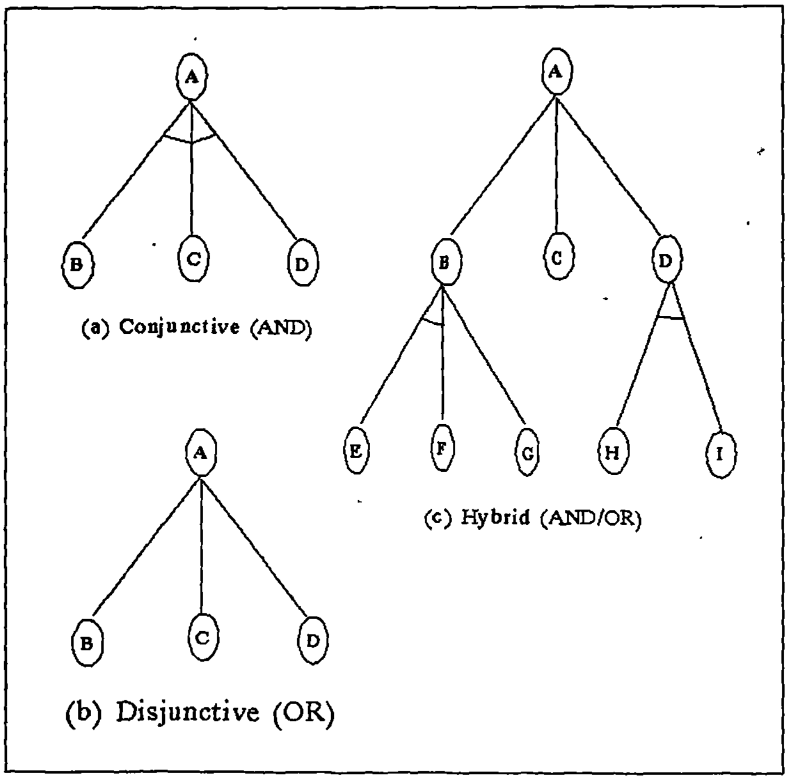


Figure 5.4 Types of hierarchy [194].

5.7.3 Physical and Functional Domains of Hierarchy in the Design Process

In the discussion on Functional Requirements (FR) and Design Parameters (DP) of the Axiomatic Approach to design, Suh [257] identified two types of hierarchy domains namely *functional* and *physical*. In the formulation of solutions to the design process the designer needs to alternate between these two domains. This is necessary as a result of an important relationship that exists between these two domains.

Functional requirements at one level cannot be decomposed into the next lower level of the functional hierarchy without first going over to the physical domain and developing a solution that satisfies the functional requirement of that particular level with all the corresponding design parameters.

Although this principle may appear obvious, it is however very important when a complex system design is being addressed. Developing solutions to hierarchical system will be in a sequential and structured manner which will avoid confusion. A particular solution will be assigned to the correct level within the hierarchy.

5.7.4 Advantages of Hierarchical Approach

The complexity of manufacturing system design decisions arises due to the inherent characteristics of design decisions themselves. Firstly, design is a series of decisions which can be made concurrently or sequentially. Secondly, the design process involves multilevel and multicriteria decision making. Hence, some means such as the hierarchy approach can be used in problems that require complex decision making processes. In fact, proficient use of the hierarchy is claimed to be a prerequisite for design or organisational success [257]. The following are some of the advantages of using hierarchy [19, 224]:

- Hierarchical representation of a system can be used to describe how changes in priority at upper levels affect priority of elements at lower levels.
- Hierarchies give great detail of information on the structure and function of a system at the lower levels and provide an overview of the elements and their purposes at the upper levels.
- Natural systems assembled hierarchically, i.e. through modular construction and final assembly of module, evolve much more efficiently than those assembled as a whole.

- Hierarchies are stable and flexible; stable in that small changes have small effect and flexible in that additions to a well-structured hierarchy do not disrupt the performance of the system.
- Quality, quantity and direction of the relationships are known and clearly recognised.
- Sequence of interactions between decisions is well defined.

5.8 The Hierarchy of Requirements for Manufacturing Systems Design

The design and specification of manufacturing systems is a difficult and complex task as manufacturing systems consist of a complex network of physical entities, decision making and information flows. The permutations and combinations in terms of their links and relationships are boundless. Furthermore, the system needs to fulfil a host of requirements that occur either at operational, tactical or strategic level. To overcome these complexities, it is proposed that the requirements be decomposed and structured in a hierarchy.

The discussion in the previous section has shown that the hierarchical view of systems requirements provide a viable approach to the solution of the design and analysis of manufacturing systems. This section will develop this theme, by elaborating on the types of requirements and the nature of relationships that occur between them. The identification of the requirements is the necessary first step in any design process.

5.8.1 Identifying the Requirements

Two methods have been used to identify the requirements for manufacturing system design: industrial survey and literature search. The questionnaire survey, which was carried out at the beginning of the research work was primarily intended to obtain an overview of the manufacturing system design practice within a sample of the manufacturing companies of the British industry. The specific sectors of manufacturing companies that were targeted belong to the SIC 3000-3999 group classifications. Although the main body of the questionnaire centred on the usage of methodologies and tools, part of the questionnaire (about 12.5 %) was structured in such a way that information on the motivation and requirements for manufacturing systems design was able to be gleaned. This is particularly the case with questions 1 to 5 in Section B of the questionnaire, see Appendix D. The report of the planning and findings of the survey is reported in Chapter 4.

Extensive literature search was performed on topics related to manufacturing system design, performance and evaluation in order to obtain as many parameters as possible that relate to the requirements and attributes of manufacturing systems. Some of the more significant references include [9, 189, 215, 254, 269, 296]. Table 5.2 provides the list of the requirements which have been identified and initially classified as strategic, economic, manufacturing and systems.

5.8.2 Classifying the Manufacturing Systems Design Requirements

As mentioned in Section 5.4 and shown in Figure 5.2, there are primarily two sets of requirements that manufacturing system design process need to satisfy, the customer's requirements as expressed through the product and the company requirements. The company requirements can be further subdivided into those derived from its competitive environment, and those result internally. The discussion on the dimensions of the competitive requirements that drive manufacturing system design has been carried out in detail in Chapter 2. The subject of internal requirements are very much discussed in aspects related to the ergonomics of systems design [134, 262] as well as the social and organisational issues [189, 195]. However both are not within the scope of the present work. Thus, the rest of the thesis will describe the methodology that is intended to fulfil the requirements of the customer or market, which is expressed in terms of dimensions of market requirement or competitive advantages.

Strategic	Economic	Production	Systems Parameters
Price • Low price • Better value for money Quality of products • Better features and design • Better performance and reliability Delivery • Delivery speed • Delivery reliability Flexibility • Wide product line • Custom-made product • Variable order size	Machine utilisation Direct labour Set-up time In-process inventory Manufacturing lead time Throughput rate Material movement time Tool change time Manufacturing cost Processing cost Overhead cost Maintenance cost Material cost	Part mix Design change accommodation Scheduling and control Ease of operation Routing flexibility Production capacity Design complexity Manufacturing precision Machine flexibility Material handling flexibility Variable batch size Quality inspection Quality levels	Precision parameters Table and pallet parameters Machining and spindle Automatic Tool Change Monitoring system (manuf control) CNC software Transport software System control Robot loader Loading/stocking features Compatibility

Table 5.2 Parameters influencing Manufacturing System Design

5.8.3 The Hierarchy of Requirements

Once the requirements are identified, they need to be categorised into suitable groupings or levels within the hierarchy. In consistency with the hierarchical model of manufacturing system, the requirements that are to be deployed will be categorised into five distinct levels:

Level 1: Strategic requirements
Level 2: Production system requirements
Level 3: Manufacturing system performance requirements
Level 4: Manufacturing system task requirements
Level 5: Manufacturing resource requirements

The levels reflect the degree of details that need to be analysed as decision making process is moved from the strategic level to the tactical level. The assumption here is that a requirement at one level can be met by a combination of parameters at the lower level either conjunctively or disjunctively. This means that an element at one level can fulfil the requirement of the adjacent level independently or in combination with other elements. The hierarchy of requirements is shown in Figure 5.5 and is described in the following sections. At manufacturing system level the requirements are divided into two categories, namely the performance requirements and the manufacturing system task requirements.

5.8.3.1 Strategic Requirements

The starting point for the design of manufacturing systems is in defining the set of fundamental requirements (or strategic requirements) that reflect the customer's demands, the competitive environment and the technological opportunities in which the manufacturing enterprise is operating. These requirements are specified in terms of the strategically significant measures of competitive advantages or dimensions of market requirements such as *price*, *quality*, *delivery*, and *flexibility*. The price dimension represents the requirement of competitive pricing. Delivery is meant to represent both delivery reliability and delivery speed. The dimensions of flexibility requirement expressed by the market are in the form of product variations and demand (volume) changes. Quality dimension is achieved through better product features and design, as well as better product performance and reliability.

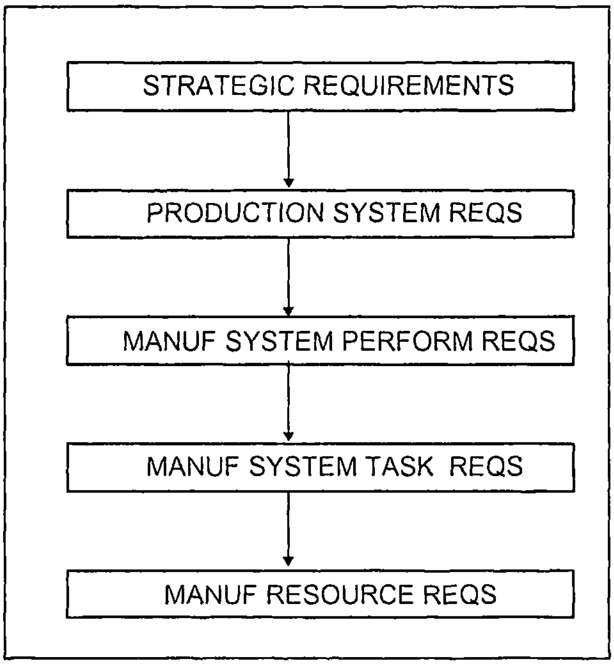


Figure 5.5 Hierarchy of Requirements for Manufacturing System Design.

A detailed discussion on manufacturing strategy and competitive priorities and their links with technology in the context of manufacturing system design was given in Section 2.5. Typically it is the responsibility of top management to define appropriate manufacturing strategy in terms of the dimensions of market requirement relevant to the business. Internal resources such as financial, technical and personnel will have to be taken into account. Due to restrictions in resources and uniqueness in the nature of the business, not every manufacturing firm is able to meet all of these dimensions of market requirement at any one time. For example in market-driven, high-technology firms where products change rapidly, the ability to introduce new products frequently may be more important than minimising cost in manufacturing strategy. Thus a suitable method need to be adopted so that the various market dimensions of the manufacturing strategy can be prioritised. One way of doing this is to arbitrarily assign numerical scales to the competitive priorities by the decision makers. There are four forms of scales that can be used in ranking alternatives in multiple criteria analysis [263]. These are nominal scale, ordinal scale, interval scale, and ratio scale. A detailed description of the scales of measurement used for multiple criteria problem is given in Appendix F. As will be described later in Chapter 6, a more reliable method in the form of Analytic Hierarchy Process [224] can be used as a technique to prioritise the competitive advantages.

5.8.3.2 Production System Requirements

The production system requirements define the measures of attributes of each of the functional areas or sub-systems in the production system that contribute towards the achievement of the strategic requirements in the overall production of the product. These sub-systems include marketing, design and engineering, purchasing, manufacturing, quality assurance and sales. The contributions of each subsystems are in the form of tasks and functions performed to meet the production system's (or company's) objectives. Figure 5.6 shows an example of the quality requirement. The tasks performed in each of the functional areas in Level II will have influence on the attainment of quality requirements at the strategic level (Level I). The functional quality attribute is in turned derived from the decomposition at the lower level of the hierarchy (Level III).

Although each functional area contributes to the realisation of a competitive priority, a decision has to be made as to which function is to be focused for further analysis down the hierarchy. The selection of the functional area for further analysis and elaboration depends on the perspective in which the study is being made. Since the focus of the present work is on manufacturing system design, the decomposition of the hierarchy of requirements will be concentrated only in issues related to manufacturing.

With respect to manufacturing (as with other functional areas) the degree or levels of contributions from other functions with respect to the manufacture of the product varies. Thus in the example for quality, the relative contributions could be in the order of: manufacturing, design, purchasing, and marketing. The degree of importance of production subsystem's attributes in meeting the strategic requirements must be determined. The initial differentiation could be based on whether the attribute can be considered as either manufacturing related and manufacturing specific, or manufacturing related but not manufacturing specific [113]. It will be shown in Chapter 6 that the planning matrix mechanism within the quality function deployment approach will be able to facilitate this differentiation.

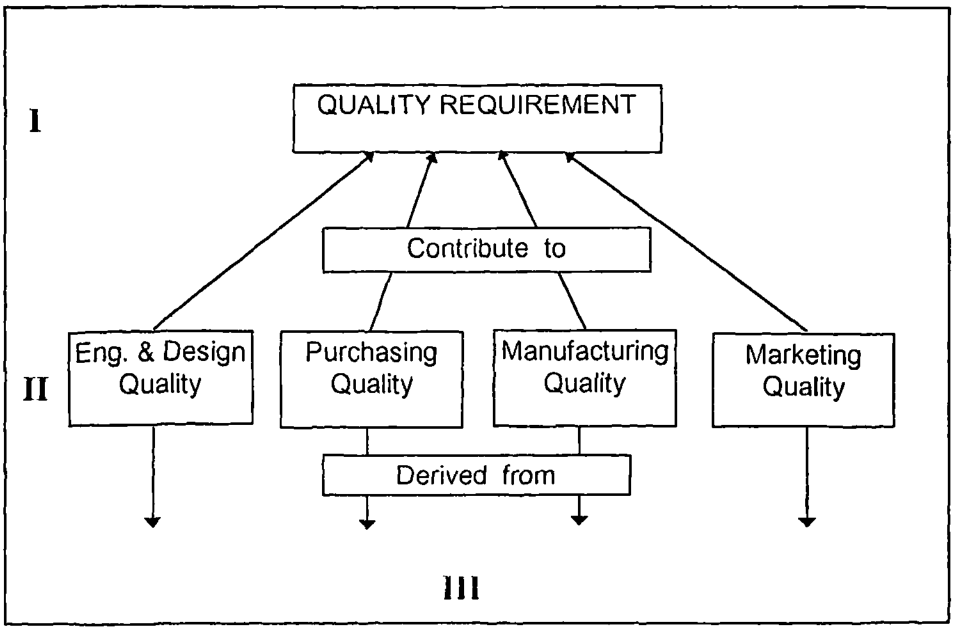


Figure 5.6 An example of decomposing the requirement. (I : Strategic; II : Production system; III: Functional systems)

5.8.3.3 Manufacturing System Performance Requirements

The manufacturing system performance requirements represent the operating targets of the manufacturing system that would need to be achieved. The targets are optimising in nature, i.e., either to be maximised or minimised. The performance of any manufacturing system is therefore a set of outputs which is usually expressed in units of measurable quantities resulting from its optimum configuration and operations. The performance measures provide a good indication of the extent of the strategic objectives by the manufacturing system. This will bring short-term perspective into focus. In addition organisational attention will be drawn to internal (manufacturing process) rather than to external questions.

The performance of a manufacturing system can be determined by the output parameters such as productivity, quality and flexibility of the system. Productivity is a measure of the manufacturing performance which indicates a firm's efficiency in converting inputs into total outputs. It is normally related to the use of resources such as materials, labour and energy. Measures used include financial as well as time performance. The elements that make up the financial measures are processing cost and system overheads. The aspect of time is represented by the throughput. An efficient or highly productive system would normally be expected to manufacture products at lower costs and shorter throughput time. At manufacturing system level, quality is an element of system performance which indicates the degree of conformance to specifications in making the products. This is measured in terms of the percentages of rejects and/or rework. Manufacturing system flexibility is a measure of performance which defines a manufacturing system's adaptability to changes in manufacturing environment.

5.8.3.4 Manufacturing System Task Requirements

Manufacturing system task requirements are the measurable attributes of the operating sub-systems of the manufacturing system such as processing equipment, material handling equipment, and system control. Again the attributes are expressed in terms of the parameters that would affect the requirements of the next higher level of the hierarchy, which in this case is the performance requirements. For example, machining time, part set-up, and queuing time would be important elements of the design requirements when system throughput is considered. The quality requirement at task level refers to the process quality, which when improved, can increase the product quality as well productivity.

The task requirements must be carefully controlled to ensure that the critical system performance requirements are achieved. In addition, when those competitive advantages are considered, particularly when the focus is on flexibility, it is not only necessary to know the organisation's current competitive strategy, but also how it might change. The novelty and predictability of changes in the environment are the major determinants of the range and response characteristics required by the manufacturing system.

5.8.3.5 Manufacturing Systems Resource Requirements

Manufacturing system resource requirements relate to the relevant information regarding the important characteristics of the manufacturing system resource such as the production or processing sub-system, material handling sub-system, and systems control. The manufacturing system resource requirements serve two purposes:

1. They represent important parameters of the sub-system elements which would contribute towards achieving the manufacturing system task requirements.

2. These are the critical characteristics or specifications of the system elements that would either provide additional dimensions or enhance the conventional criteria (such as capacity and financial justification) in determining the selection of the machine and equipment in the physical design of the system.

Different system task requirements indicate different parameters of the manufacturing resources, or different way of organising the resources. As an example, consider the cylindrical machining process where cutting speed and the tool life are related ($Vt^n = C$, for $n = 0.14 - 0.4$). To meet the time (delivery) requirement would need specifying a machine tool with higher spindle speed capacity. However quality requirements dictate that a lower speed is preferable as the relaxation in cutting speed increases the reliability of the process, reducing the probability of a breakdown or of producing defects. Hence it can be seen that by decomposing the requirements into a hierarchy, the system general resource requirements are defined and the agenda can be set to develop a program of alternative action plans. The final parameters that will be considered in the selection of sub-systems elements in the manufacturing system will not be trivial, and can be traced back to the set of competitive advantages adopted by the manufacturing company. The scope of selection criteria for the elements of the manufacturing system will not be limited to those dependent on product requirements and economic justification alone. There will be an added dimension of strategic perspective.

5.8.4 Description of the Hierarchy of Requirements

By virtue of the hierarchical structure of the requirements, each of the requirement at one level can be accomplished by a combination of elements, either conjunctively or disjunctively, at the lower level of the hierarchy. There may be some overlapping when the same element at one level can contribute to more than one requirements in the level immediately above it. The following is a description of the hierarchy for each of the strategic requirements. The discussion will concentrate on how the various factors that contribute towards the strategic requirements are related within the hierarchy. Detailed discussion of each of the competitive advantages is given in Chapter 2.

5.8.4.1 Cost Requirement

The external demand for a competitively priced product means that there is a need for low manufacturing cost in order to maintain a given profit margin. As shown in Table 5.3, at the production system level, the overall cost of the product is basically the sum of the costs incurred at each of the functional areas of design and engineering, procurement, manufacturing, marketing and sales, as well as those associated with the general administration of the company. At the manufacturing performance level, the manufacturing cost requirements are aggregated into processing cost and overheads. The high degree of significance given to the overhead cost reflects the advanced manufacturing systems involved. To meet these performance requirements, the system design must accomplish the optimum design parameters which represent the manufacturing system task requirements. Processing cost is influenced by materials, labour, tooling and fixture costs. The overhead cost on the other hand is made up of materials handling, quality inspection, maintenance etc. Finally these costs can be reduced by correctly selecting and integrating the variables that make up the manufacturing system resource requirements.

5.8.4.3 Quality Requirement

The overall quality requirement at the strategic requirement of the market, can be interpreted into many dimensions, as shown in Table 2.5. Within the production system it is influenced by the activities in the design and engineering, purchasing, manufacturing as well as marketing and sales functions. Within each function there are subfunction elements that need to be considered. For example, at the product planning and product design activities within the design and engineering quality is governed by the degree to which technical specifications of the product satisfies the customer demands.

Similarly, the efficiency and effectiveness of material and component procurement activities will affect purchasing quality. If manufacturing related and manufacturing specific activities only are considered, then the activities within manufacturing function that are relevant at Level 2 will involve process design, production and quality control. In the process design and production, manufacturing quality depends on the degree to which the product, when made available to the customer, conforms to the specifications. In the next lower level, Level 3 of the hierarchy, parameters such as system reliability, percentage rejects and percentage rework that influence the performance of the manufacturing system design requirements are grouped.

Level 1: Strategic requirements	Level 2: Production system requirements	Level 3: Manufacturing system performance requirements	Level 4: Manufacturing system task requirements	Level 5: Manufacturing system resource requirements
Price	Design and engineering			
	Purchasing		Materials; labour; tooling and fixture cost;	
	Manufacturing cost	Processing cost	Material handling cost; quality inspection cost; m/c set-up cost; maintenance cost; inventory cost; number of operations; machine utilisation; part mix; batch size	Processing equipment parameters; Material handling parameters; Control system parameters
		Manufacturing Overheads		
	Marketing and sales			
	Administrative			

Table 5.3 Decomposition of price requirements

Level 1: Strategic requirements	Level 2: Production system requirements	Level 3: Manufacturing system performance requirements	Level 4: Manufacturing system task requirements	Level 5: Manufacturing system resource requirements
Quality	Design and engineering *(Product planning; product design)*			
	Purchasing *(Material and component procurement)*			
	Manufacturing *(Process design; production; quality control)*	Percentage rejects; percentage rework; system reliability	Machine reliability; process capability; control of process	Processing equipment parameters; Material handling system parameters; Control system parameters; quality control methods, quality assurance programs
	Marketing and sales *(Distribution and field service)*			

Table 5.4 Decomposition of quality requirements

Aiming to achieve the optimum values of these performance requirements will ensure attainment of the production system requirements, which is the manufacturing quality. Thus in Level 4 of the hierarchy those parameters of the individual subsystems such as machines, material handling equipment and control system that influence the performance of the system are grouped as manufacturing system task requirements. Examples include machine reliability, process capability and materials handling reliability. The specific tools and techniques that are relevant to achieve the manufacturing system design requirements are grouped in Level 5. As far as quality is concerned this include the specific tools such as Statistical Process Control (SPC).

5.8.4.3 Delivery Requirement

The decomposition of the delivery requirement is shown in Table 5.5. There are two aspects to delivery requirement, namely the delivery reliability and the delivery speed. These two aspects of delivery requirement are influenced internally within the manufacturing organisation by the time associated with product design and development phase and manufacturing phase, as well as the interaction between the two. Improvement in design time is achieved by techniques such as computer aided design and Failure Mode and Effect Analysis (FMEA). The lead time from design to manufacturing can be reduced by focusing on the integration of design and manufacture, where techniques such Design for Manufacture and Assembly (DFMA), computer aided manufacture and QFD are relevant. Efforts on reducing manufacturing lead time involves considerations of capacity, scheduling and inventory holdings. Techniques such as MRPII, JIT and OPT are normally used. To meet the delivery speed requirement greater emphasis is placed on manufacturing processes which can respond to this requirement. This is on top of the efforts previously mentioned.

At the production system level the delivery requirement is influenced by the lead times associated with design and engineering, purchasing, and manufacturing. Within each functional area the problem can be analysed in greater detail, and appropriate tools and techniques can be used to improve the lead times. Within the manufacturing related and manufacturing specific domain, the delivery requirement is further decomposed into the manufacturing system performance, system task requirement and systems resources. The performance measures include system throughput, system utilisation, and inventory level. These can be achieved by the tasks or functions performed such as processing time, and workpiece set-up and handling time, which in turn can be achieved through the manipulation of the specific parameters of the manufacturing resources.

5.8.4.4 Flexibility Requirement

Flexibility is the term used to describe the ability to respond effectively to changing environment. In the strategic context manufacturing flexibility is the ability of a manufacturing organisation to adapt its resources effectively in response to changing market conditions, significantly epitomised by variability in product demands. The fulfilment of the flexibility requirement at the strategic level is to be achieved by the interactions of the flexibilities at the lower level of the requirements hierarchy as shown in Table 5.6. This notion of the structural relationships between the various types of flexibility is adopted from models that have been proposed by several authors [66, 235, 243, 264].

At the strategic level, the flexibility requirement is expressed in terms of product mix changes and volume demand variations. This division is necessary as each type of flexibility demand requires different combination of variables down the hierarchy. In order to address the requirements of flexibility at the strategic level, another two types of flexibilities are identified at the production system level: market flexibility, which is the ease with which changes in the market environment can be responded, and production flexibility, which is the universe of part types that can be produced without undergoing major changes such as addition of major capital equipment. While the latter can be only be addressed through technological means, the former can be achieved both by technological and non-technological means such as labour and infrastructure. In this methodology, the scope will be limited to technological aspects.

Level 1: Strategic requirements	Level 2: Production system requirements	Level 3: Manufacturing system performance requirements	Level 4: Manufacturing system resource requirements	Level 5: Manufacturing system elements
Delivery (reliability and speed)	Design and engineering lead time Purchasing lead time			
	Manufacturing lead time	Throughput System utilisation Queuing time	Machining time; workpiece handling time; tool handling time; machine set-up time; machine utilisation; inventory level;	Processing equipment parameters; Material handling system parameters; Control system parameters
	Marketing and sales (distribution lead time)			

Table 5.5 Decomposition of delivery requirements

Level 1: Strategic requirements	Level 2: Production system requirements	Level 3: Manufacturing system performance requirements	Level 4: Manufacturing system task requirements	Level 5: Manufacturing resource requirements
Flexibility	Design and engineering			
	Purchasing			
	Manufacturing: Production flexibility Market flexibility	Volume flexibility Process flexibility Product flexibility Routing flexibility Expansion flexibility	Machine flexibility Material handling flexibility Control system flexibility	Processing equipment parameters; Material handling system parameters; Control system parameters
	Marketing and sales			

Table 5.6 Decomposition of flexibility requirements.

Five types of flexibility are defined at the manufacturing performance level that will determine the effectiveness of the manufacturing system. These are process flexibility, product flexibility, volume flexibility, routing flexibility, and expansion flexibility. Brief definitions of these flexibilities are given in Table 5.7. Both the range and response aspects of these flexibilities [244] are relevant in the present context. The systems task requirements that can be manipulated to achieve flexibilities at the performance level include machine and material handling flexibilities, as well as the level of integration of the system. At the most basic level these are influence by machine control, tooling and material handling variables.

Flexibilities	Description
Process	The set of part types that the system can produce without major set-up.
Product	The ease with which new products can be added or substituted for existing parts.
Volume	Ability of the manufacturing system to be operated profitably at different output levels.
Routing	The ability to produce a part by alternative routes through the system.
Expansion	The ease with which the capacity of a manufacturing system can be increased when needed.

Table 5.7 Types of flexibility at manufacturing performance level.

5.9 Summary

The chapter has elucidated the framework for defining manufacturing system design requirements. The suitability of adopting the principles of the QFD approach was justified by comparing the QFD concepts with the major criteria of manufacturing system design methodology. Based on the need to fulfil the strategic requirements, each of the competitive advantages of price, quality, delivery and flexibility is decomposed into a set of subordinate requirements which are arranged hierarchically.

The advantages of using the hierarchical approach have been presented. Detailed accounts of the design requirements were given in two supplementary manners: the description of each hierarchical level and the description of each of the strategic requirements. These breakdowns of the requirements will be utilised in the deployment of the system functions, which will be described in the next chapter.

CHAPTER 6

MANUFACTURING SYSTEM DESIGN REQUIREMENTS DEPLOYMENT

6.1 Introduction

This chapter discusses the stages and steps involved in deploying the hierarchy of system function requirements which have been established in Chapter 5. The requirements in one level of the hierarchy are fulfilled by a combination of parameters at the lower level. The deployment from one level to another is called a requirements deployment phase. The relationships between the parameters in the two adjacent levels are defined by the degree of importance of the requirements in the higher level, and the strength of relationships between the requirements and the parameters that fulfil those requirements in the lower level of the hierarchy. Thus if the degree of importance of one requirement is high, and the strength of the relationship with a particular parameter is also high, this will result in the parameter having greater technical importance and being deployed into the next phase. The relationships and the deployment of the requirements are graphically represented through a series of planning matrices which have been adapted from the Quality Function Deployment approach. The deployment process is carried out using the QFD/CAPTURE package which runs on a personal computer.

6.2 Multiple Criteria Decision Making Problems

Before discussing in detail the deployment phases, it is appropriate to briefly describe the nature of multiple criteria decision making problems which represent the core of the methodology.

Multi-criteria decision problems normally involve conflicting objectives (or other parameters) which may be of varying importance to the decision maker. Depending on the nature of the problem, the relativity of importance can be conceptualised in several ways. These include [263]:

- all objectives are indispensable and no trade-off is possible - this is the case of no solution;
- all are indispensable up to some limiting value, but beyond that limit additional quantities for all objectives are of little, or no value;
- all are indispensable up to some limiting value, and beyond that value, trade-off is possible;
- all are indispensable but others are traded off indefinitely;
- all objectives are dispensable, all can be traded off.

The above listing of possibilities are arranged in the order of decreasing degree of difficulty in terms of finding a solution. Most multicriteria decision making techniques are developed along the last possibility. This is the case with the deployment of manufacturing system design requirements. In fulfilling the requirements at one level, only some of the parameters at the lower level are selected depending on a given set of criteria.

6.3 Phase 1 : Strategic Requirements Deployment

The aim of this phase is to relate as accurately as possible the strategic requirements of the external customer to the organisation of the company's resources and capabilities. The external or customer's requirements are represented by the dimensions of market requirements or competitive advantages that the manufacturing company seeks to fulfil. These strategic decisions are made at the corporate level within the business hierarchy as part of the overall business planning. Section 2.5 discussed in detail the relationship that exists between manufacturing strategy and technology decisions. Figure 6.1 shows the layout of planning matrix for the first phase of the methodology. The flow chart for the problem solving steps involved in Phase I is shown in Figure 6.2, and is described as follows.

Once identified and agreed the strategic requirements are listed in the WHAT's room of the first planning matrix. The strategic requirements may not have the same degree of importance for a given company in any particular market setting. Depending on the type of market and competition that it is in, the company may assign a unique priority to each of the competitive priority. The degree of priority is entered in the intersection of WHAT's row and WHY's column of the planning matrix.

WHATs vs. HOWs Legend	
Strong ●	9
Moderate O	3
Weak Δ	1

	Production System Requirements	Design and engineering cost	Purchasing cost	Marketing and sales cost	Administrative cost	Manufacturing cost	System procurement cost	Design and engineering quality	Purchasing quality	Manufacturing quality	Marketing and sales quality	Production flexibility	Market flexibility	Design and development lead time	Purchasing lead time	Manufacturing lead time	Distribution lead time	Priority
Competitive priorities																		
Low price																		
High quality																		
Delivery reliability																		
Delivery speed																		
Product variety																		
Volume changes																		
Direction of improvements		↓	↓	↓	↓	↓	↓	↑	↑	↑	↑	↑	↑	↓	↓	↓	↓	
Absolute importance																		
Relative importance																		

PM1
1.11.95

Figure 6.1 Planning Matrix 1 (Competitive priorities deployment)

The company requirements that are deemed necessary to meet the strategic requirements are aggregated as production system requirements in order to be consistent with the model of the manufacturing system adopted. At this level of the model the HOW's room in the planning matrix will show all the decision parameters contributed by the various functional areas of the production system. What this means is that these parameters are considered to be relevant in meeting the strategic demands of the market. As an example, consider the strategic requirement of 'Low Price'. Hence, to meet the requirement of low price, the manufacturing company should seek efforts to optimise cost influencing activities in most of the functional areas within the overall production system, such as design and engineering, manufacturing and logistics. Depending on the nature of the manufacturing firm, the contribution of the variables from each function differs in relative terms. The relative significance of the parameters in influencing the requirement of price is determined in the matrix relationships between the WHAT's and the HOW's.

6.3.1 Problem Solving Steps for Phase 1

The problem solving steps for phase 1 are shown in the form of a flow chart in Figure 6.2. These are described as follows:

1) Identify the strategic requirements that need to be met in order for the company to be competitive. These are then entered into the WHAT's room of the planning matrix. As shown in Figure 6.1, the strategic requirements of price, quality, product variety, volume changes, delivery speed and delivery reliability are entered in the left column of the planning matrix. Each of these requirements need to be analysed in terms of what it means in terms of the performance measures and technical parameters of the manufacturing system.

Prioritise the WHAT's by assigning the degree of importance to each of the strategic requirements. The assumption made at this point is that it is impossible for a firm to excel in all of them simultaneously. This could be achieved by the brainstorming process of a team involving the various departments concerned with the design of the manufacturing system. To improve the quality and accuracy of judgements the Analytic Hierarchy Process (AHP) method [224] can be used to arrive at the degree of importance or priority of the WHAT's. The principle behind the AHP is that the degree of satisfaction of any objective can be expressed as a number, or utility vector. If the objective is split into sub-objectives, the importance of each of these on the objective can be calculated. It follows that the degree of satisfaction of each sub-objective can be calculated, and hence the overall utility vector for each alternative. Details of the method are described in Appendix G.

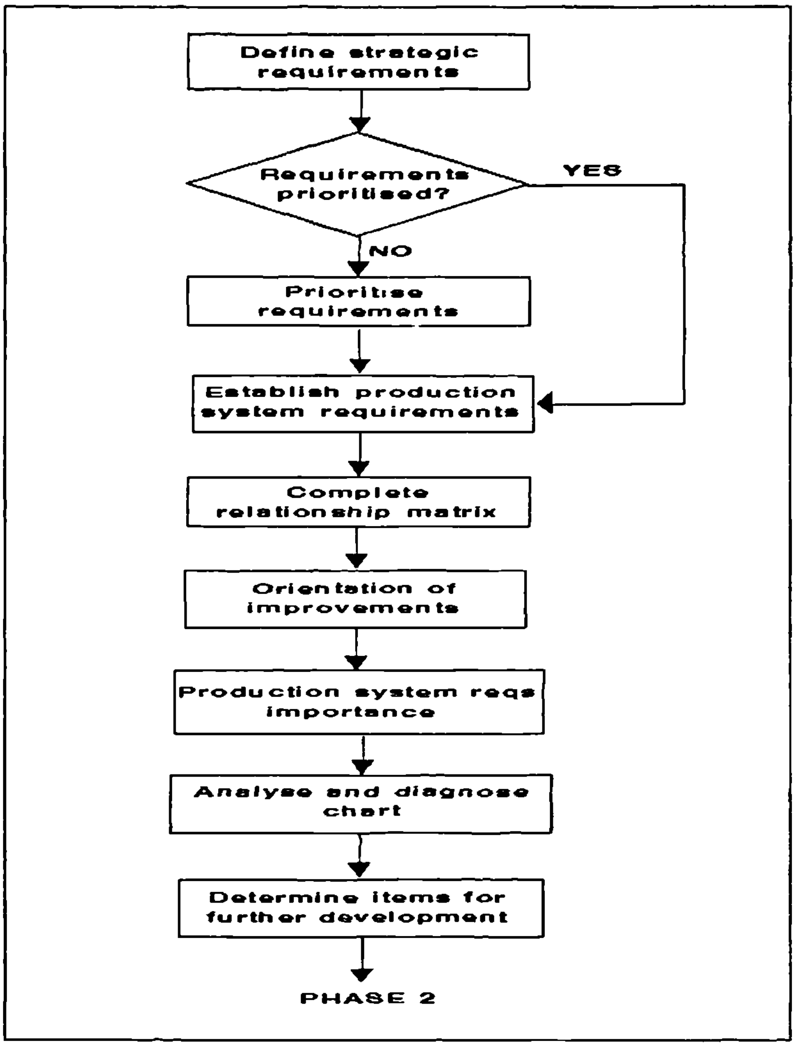


Figure 6.2 Flowchart for problem solving steps in Phase 1.

3) Identify and list in the HOW's room the production system parameters that exert influence on each of the strategic requirements.

4) Establish the nature of relationships between the WHAT's and the HOW's in the planning matrix. In the matrix this is the intersection of the WHAT's row and the HOW's column. Depending on the degree of contribution of the production system functions towards achieving the requirements, the relationship between a WHAT and a HOW is categorised into three types: strong (numerical value of 9), moderate (numerical value of 3), and weak (numerical value of 1). These values have been recommended by the majority of the QFD literature [4]. The use of such ratio scale provides a means of achieving a good variance between important and less important items. Recalling the feature of a hierarchy where an element in a level can be related conjunctively and disjunctively to the elements in the level below, the same principle applies in this case. As an example, consider the case for quality and low price as shown in Figure 6.3. Besides the obvious cost contributions from the cost related parameters in the production system, quality parameters can also influence *the low price requirements. Hence there are* overlapping of parameters at the lower level of the hierarchy in fulfilling the requirements of the higher level. In determining the strength of the relationships between a HOW and a WHAT, the judgement is to be based on the extent to which the production system parameters can impact the strategic requirements.

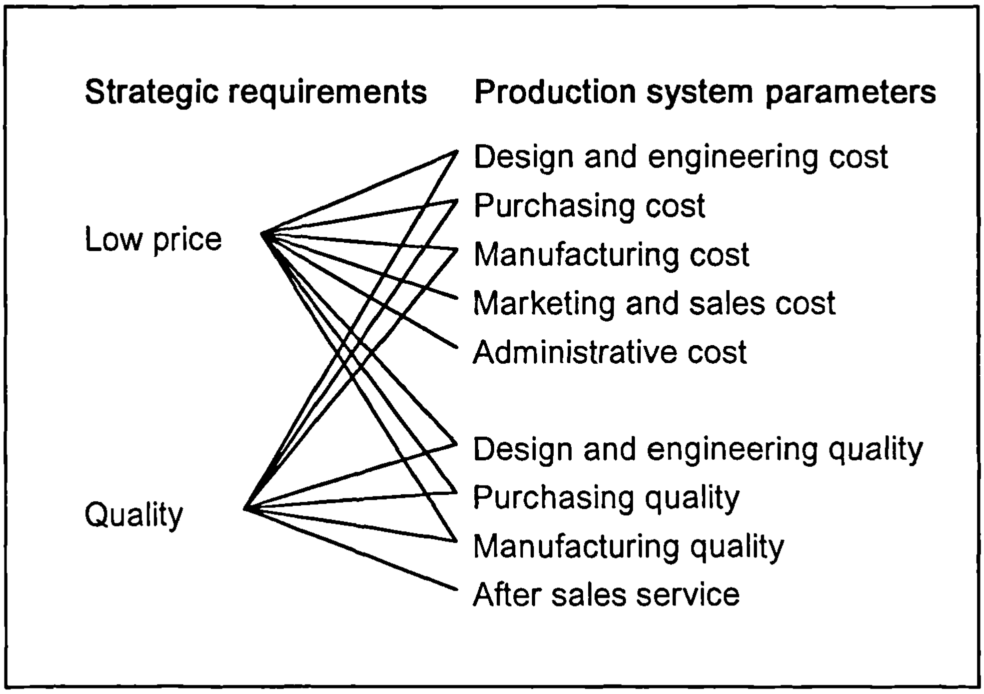


Figure 6.3 Example of interdependence of requirements.

5) Evaluate the technical importance ratings of the HOW's. These are the combination of the degree of priority of the strategic requirements (based on the priority values evaluated by AHP) and the strength of the relationship between the production system parameters and the strategic requirements. The importance ratings are expressed in two ways in the planning matrix: (a) Actual value, and (b) Relative value.

Actual value of importance rating = Σ[(Relative importance of WHAT's) X (Strength of WHAT's vs HOW's)].

Relative value of importance rating = Actual value of importance rating/Total value of importance rating.

The actual value is the numerical value calculated using the formula, and it does not have any significant in so far as indicating the degree of importance of the HOW's. Thus the relative values will be used in determining to what degree of importance each of the HOW's has.

6) To improve the communication and better understanding of the information provided by the planning matrix, the orientation of each of the elements in the production system functions is included in the matrix. The orientation is defined as the ideal direction to optimise each HOW, i.e., either maximise ↑ or minimise ↓.

7) Select the production system parameters (HOW's) for deployment into the next phase. The criteria for selection are: relevancy and importance. Relevancy indicates the areas of emphasis in which the methodology is to proceed. In the case of manufacturing system design, only those specifically related to the actual production will be considered. The degree of the relative importance of a HOW is a measure of the combined effect of the priority level of the WHAT and the strength of the relationship between a WHAT and a HOW. Thus items like design cost and design quality are not deployed further into the next phase as they are not specifically related to manufacturing.

6.4 Phase 2 - Production System Requirements Deployment

The objective of this phase is to translate the production system requirements to the performance parameters of the manufacturing system. This is achieved by deploying the production system characteristics that have significant degree of contributions in accomplishing the strategic objectives into the WHAT's room of the second planning matrix. It is important to note that since the present analysis is only in the context of manufacturing systems, only those parameters which are manufacturing related and manufacturing specific have been deployed from previous planning matrix. The relative degree of importance for the production system requirements are carried from the previous phase so that the continuity and relationship are maintained.

Manufacturing system performance parameters that influence the production system performance requirements which have been identified (Chapter 6) are listed in the HOW's room. These are the performance measures of the manufacturing system which relate to manufacturing cost, manufacturing lead time, manufacturing quality and flexibility. Figure 6.4 shows the contents of the planning matrix of Phase 2.

6.4.1 Problem Solving Steps for Phase 2

The problem solving steps are shown in Figure 6.5.

1) The selected production system parameters become the requirements for next phase and are entered in the WHAT's room of the planning matrix 2.
2) Transfer the importance values into the WHY's room. The numerical values are rescaled in order to maintain numbers of convenient size. An ordinal scale of 1 - 5 is used in this case, with 5 for the most important and 1 for least important.
3) Determine the manufacturing system concept that needs to be developed and implemented. This step refers to the selection of the most appropriate type of the manufacturing system, taking into account the product design and demand. Chapter 2 has presented a range of manufacturing systems that can be selected. Section 6.4.2 outlines a methodology to select a system concept.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

	Manufacturing System Performance Requirements	Processing cost	Manufacturing overheads	Percentage rejects	Rework	Warranty cost	System reliability	System throughput	Non-operation time	System utilization	Volume flexibility	Process flexibility	Product flexibility	Routing flexibility	Expansion flexibility	Relative importance
Production System Requirements																
Design and engineering cost																
Purchasing cost																
Marketing and sales cost																
Administrative cost																
Manufacturing cost																
System procurement cost																
Design and engineering quality																
Purchasing quality																
Manufacturing quality																
Marketing and sales quality																
Production flexibility																
Market flexibility																
Design and development time																
Purchasing lead time																
Manufacturing lead time																
Distribution lead time																
Direction of improvements		↓	↓	↓	↓	↓	↑	↑	↓	↑	↑	↑	↑	↑	↑	
Absolute importance																
Relative importance																

PM2
1.11.95

Figure 6.4 Planning matrix for Phase 2.

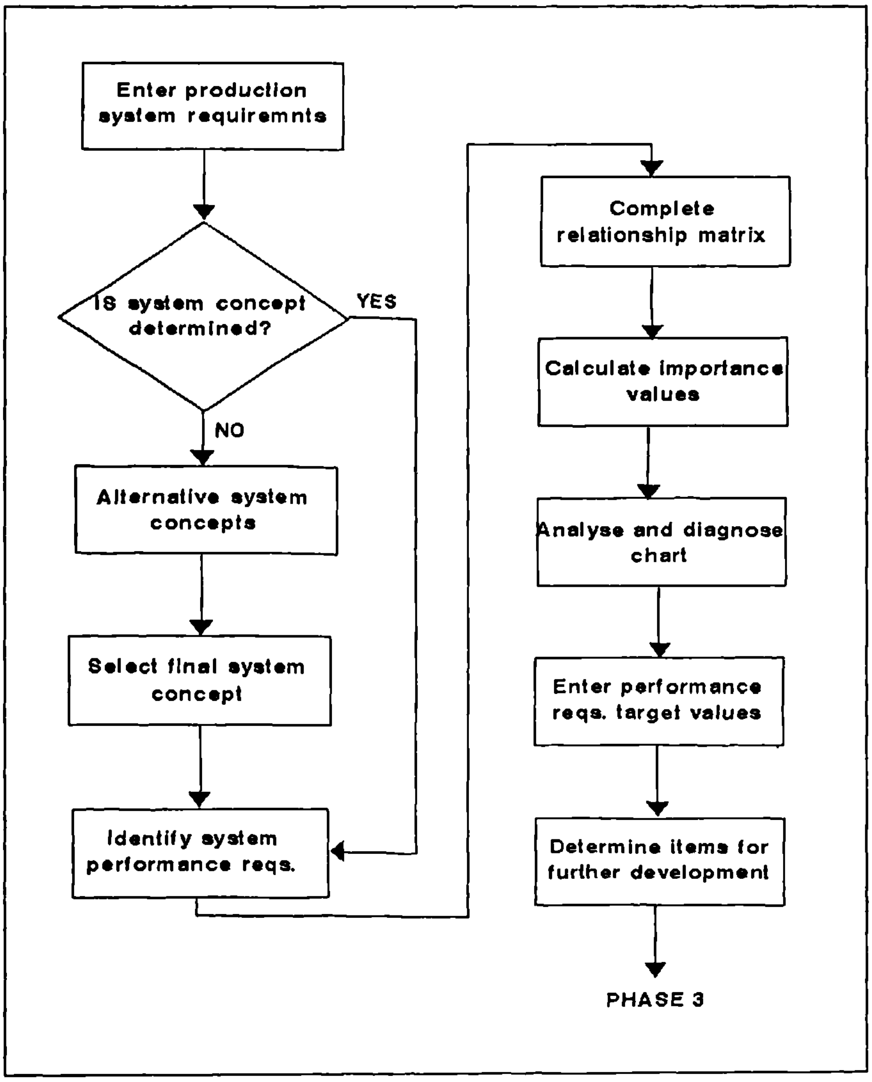


Figure 6.5 Problem solving steps for Phase 2.

4) Identify system performance requirements and enter them into the HOW's room.
5) Determine the relationship between the WHAT's and the HOW's, and complete the relationship matrix.
6) Calculate the relative importance values.
7) Establish measurable values for the HOW's and enter the performance requirements target values that need to be achieved.
8) Analyse and diagnose the planning matrix.
9) Determine items for further development.

6.4.2 Concept Selection

An important objective of manufacturing system design is to ensure that the system being designed meets the demands of the competitive market. Thus the selection of an optimal system can be considered as an economic design problem at the strategic planning level. It is preceded by the screening process which involves a preliminary economic evaluation of alternatives in order to identify inefficient designs. The selection procedure is based on the following parameters: technical (e.g. technological progress), financial (e.g. interest rate), internal (e.g. inventory levels) and external (e.g. product life cycle). Furthermore the long term strategic issue such flexibility should be considered at this stage.

One of the most direct and less mathematical approaches to concept selection is the use of Pugh's concept selection approach [211]. In this approach one alternative concept is chosen as a reference or datum. Each of the other alternatives are compared to the datum using each of the selection criteria. This comparison is made by assessing if the alternative is clearly better, clearly worse, or about the same. As in QFD processes, this approach is a team effort.

6.5 Phase 3 : Manufacturing System Performance Deployment

The objective of this phase is to establish the relationships between the performance requirements and the task requirements of the manufacturing system. In this phase manufacturing system performance requirements become the input into the WHAT's room of the planning matrix. The HOW's room consists of the relevant task requirement parameters of the sub-systems. The importance ratings of the manufacturing system performance requirements are carried forward from the previous phase. Based on the strength of relationship between the WHAT's and the HOW's, as well as the relative importance of the performance requirements the output of this phase would be a set of important and relevant manufacturing system design parameters of the processing and material handling which are the physical sub-systems, production planning and control which is decisional sub-systems, and system and cell control which is informational sub-system. Figure 6.6 illustrates the planning matrix for Phase 3.

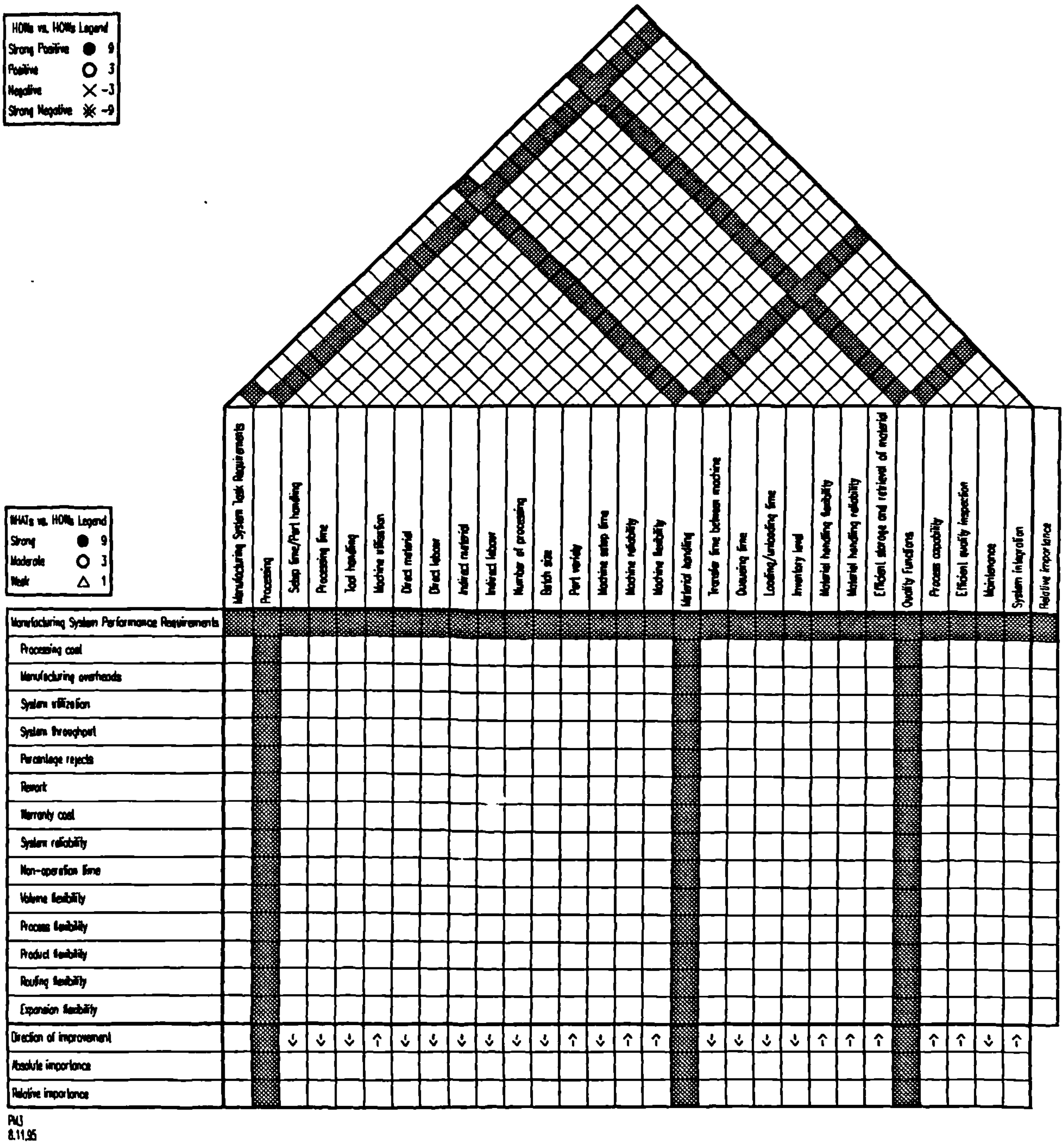


Figure 6.6 Planning matrix for Phase 3

6.5.1 Problem Solving Steps for Phase 3

Figure 6.7 shows the problem solving steps involved in phase 3.

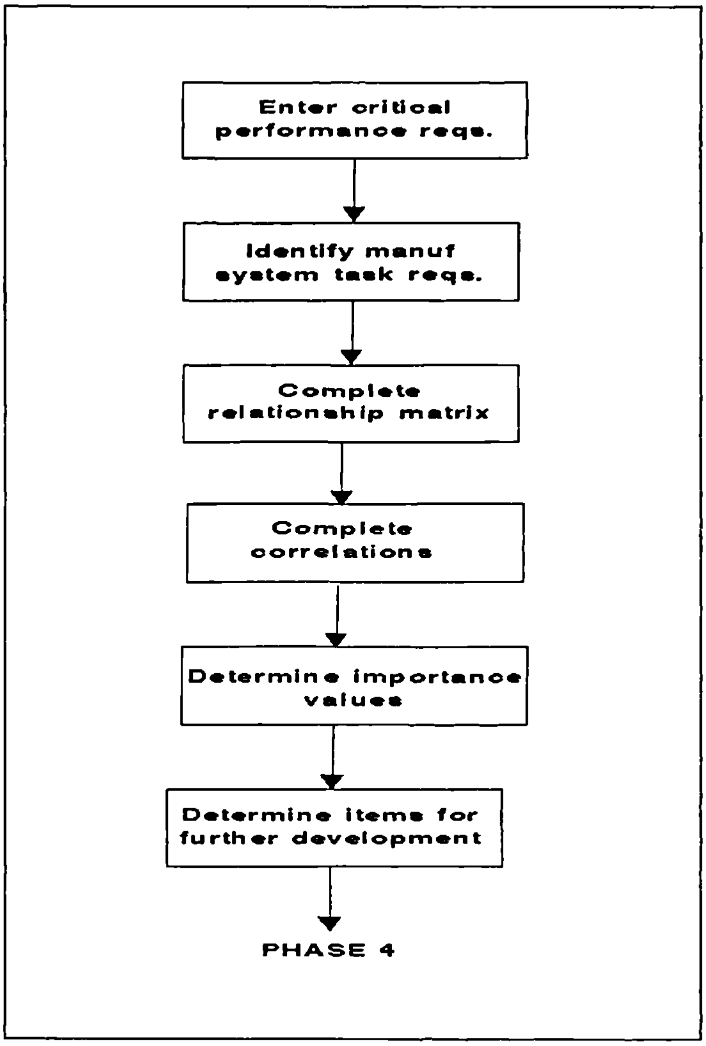


Figure 6.7 Flow chart for problem solving steps in Phase 3.

1) Enter the selected manufacturing system performance requirements in the WHAT's room.
2) Transfer the importance values of the performance requirements into the WHY's room. The numerical values are rescaled in order to maintain numbers of convenient size.

3) Identify the manufacturing system task requirements and enter them into the HOW's room.
4) Determine the relationship between the WHAT's and the HOW's, and complete the relationship matrix.
5) Calculate the importance values.
6) Evaluate the correlation that exist among the HOW's.
7) Establish measurable values for the HOW's and enter the manufacturing system task requirements target values that need to be achieved.
8) Evaluate the organisational difficulty that would be faced in implementing the design requirements. The organisational difficulty will take into account the technical difficulty as well the organisational barriers to meet the requirements.
9) Analyse and diagnose the planning matrix.
10)Determine items for further development.

6.6 Phase 4 : Manufacturing System Task Deployment

In this phase the objective is to map the selected manufacturing system task requirements from phase three into the technological parameters of the resources of each of the subsystems. The output from this phase will be used to aid decisions on the selection of suitable equipment from the spectrum of technologies available. Figure 6.8 shows the planning matrix for phase 4.

The parameters of the manufacturing system elements are classified into appropriate parameter groups, as shown in Table 6.1. The concept of parameter groups which have been introduces by Arbel and Seidman [9] has been modified and used. The groups developed by them were based on flexible manufacturing system consisting of machining centres. However, the principles are extended in the present work to include those parameters for turning as well as the material handling system. Based on the relationships that exist between manufacturing system design requirements and the parameter groups, phase four provides additional sets of criteria to be used in the selection of machines and equipment.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

	System element attributes	Machining centre	Precision parameters	Table and pallet parameters	Machining and spindle	Automatic tool change	Monitoring system	CNC software	CNC Lathe	Precision parameters	Turning parameters	Spindle parameters	Tooling	Monitoring system	CNC software	Transportation	Transport parameters	Load parameters	Transport software	Space requirements	Loading/unloading.	Loading parameters	Controller	System controller	Structure	Compatibility	Production planning and control	Relative importance
Manufacturing System Task Requirements																												
Processing																												
Setup time/Part handling																												
Processing time																												
Tool handling																												
Machine utilisation																												
Direct material																												
Direct labour																												
Indirect material																												
Indirect labour																												
Number of processing																												
Batch size																												
Part variety																												
Machine set-up time																												
Machine reliability																												
Machine flexibility																												
Material handling																												
Transfer time between machine																												
Queueing time																												
Loading/unloading time																												
Inventory level																												
Material handling flexibility																												
Material handling reliability																												
Efficient storage and retrieval of parts																												
Quality Functions																												
Process capability																												
Efficient quality inspection																												
Maintenance																												
System integration																												
Absolute importance																												
Relative importance																												

PM4
17.11.95

Figure 6.8 Planning matrix for Phase 4.

The technical or engineering attributes of the subsystem which form the criteria can be traced back to the initial strategy adopted. An example for the relationship between robot attributes and performance of a production system is shown in Figure 6.9. Hence the criteria will supplement the selection of the processing requirements, material handling requirements, and system control requirements which are normally limited to part specifications and financial constraints.

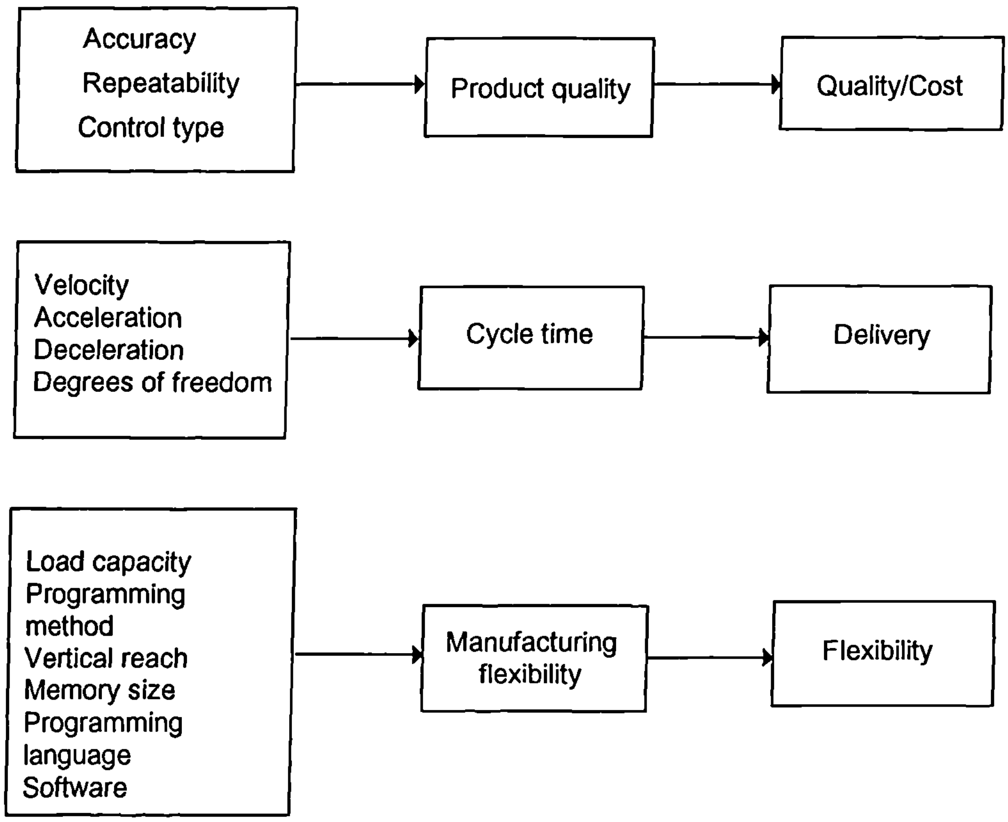


Figure 6.9 An example of tractability of technical parameters to strategy.

Sub-system elements		Parameter groups	Parameters
Processing	Machining centre	Precision parameters	Table indexing accuracy; indexing angle; positioning accuracy; pallet positioning accuracy; positioning repeatability;
		Table and pallet parameters	Table size; number of pallet changers; pallet change time; table load capacity; X-Y-Z stroke
		Machining and spindle	Speed range; maximal feed-rate; Spindle torque; rapid traverse; cooling system;
		Automatic Tool Change	Magazine capacity; tool selection system; tool change time; max. tool dimensions (diameter and length)
		Monitoring system	Tool life monitoring; tool breakage detection; adaptive feed-rate control; spare tool selection; machine failure detection; machine time monitoring; In/post process gauging; Automatic centering;
		CNC software	CAM language; automatic programming, self diagnostic/alarm; data logging; background programming
	CNC turning	Precision parameters	Accuracy; Repeatability (in x and z); Turret indexing
		Turning parameters	Max dia; ISO spindle bore; turning length; nos. of axis; throughbore dia;
		Spindle parameters	Speed range; spindle motor; rapid feeds (z and x axes); working feed; spindle indexing, 'C' axis
		Tooling	Turret capacity; tool change time (indexing time); Automatic tool change; Live tooling;
		Monitoring system	Tool wear/breakage monitoring; In/post-process gauging;
		CNC software	Programme storage; background programming;

Table 6.1(a) Parameter groups for manufacturing system resources (processing).

Sub-system elements		Parameter groups	Parameters
Material handling	Transportation	Transport parameters	Speed, distance moved, random movement, accuracy
		Load parameters	Weight, size, stability
		Transport software	Scope of monitoring, control and communications compatibility
		Space requirements	Space, accessibility, safety, expandability
	Loading/ unloading	Loading parameters	Load capacity; speed; pallet size; nos. of pallets; accuracy
		Controller	Communications/compatibility
Integration	System controller	Structure	Communication topologies, hardware, software
		Compatibility	Machine tools; transport systems; computer control; data communication;
	Production planning and control		Production scheduling; machine loading; material control; data base management; management interface; production planning; system upgrade

Table 6.1 (b) Parameter groups for manufacturing system resources (material handling and integration)

6.6.1 Problem Solving Steps for Phase 4

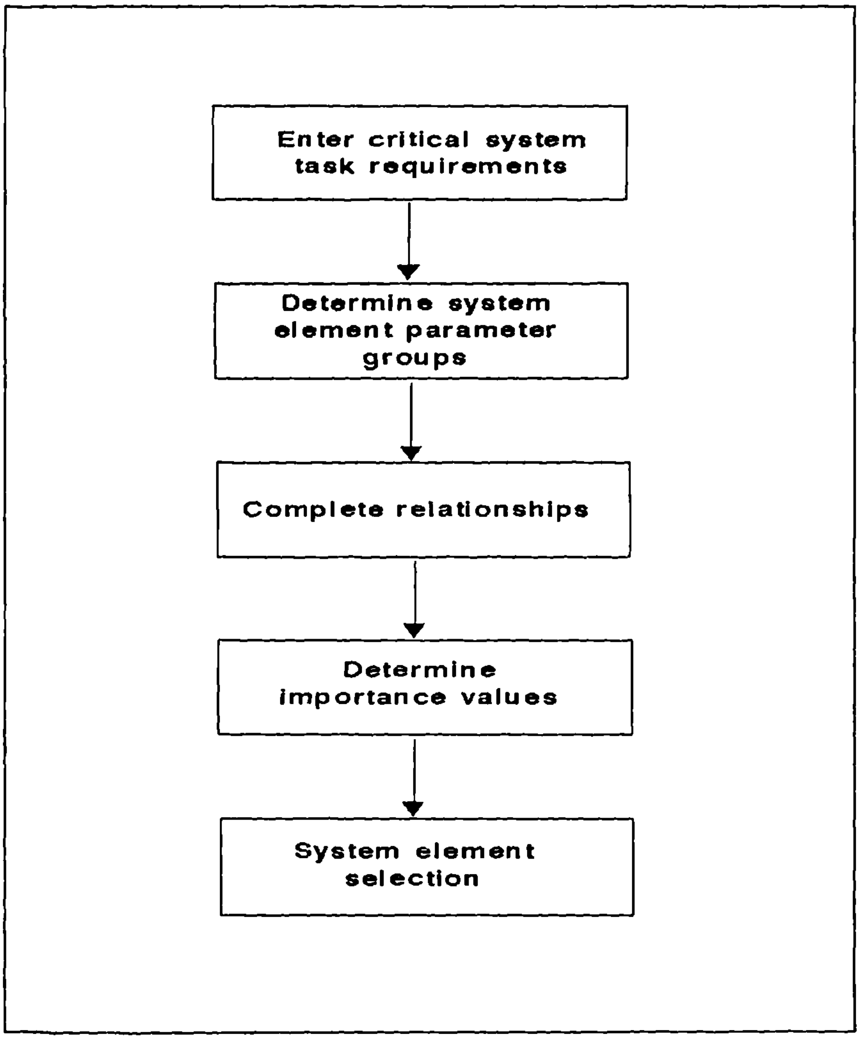


Figure 6.10 Flow chart for problem solving steps in Phase 4.

1) Enter the selected manufacturing system task requirements into the WHAT's room of the planning matrix. The values of the relative importance which have been ranked are carried from the previous phase.
2) For each sub-system identify the parameters that influence the subsystem functions. These are categorised into parameter groups. The use of parameter groups has overcome the problem of having to deal with a lot of variables.

3) Establish and complete the relationships that exist between the manufacturing system requirements and the parameter groups.
4) Determine the degree of importance of the parameter groups.
5) Use the parameter groups for system element selection.

6.7 Manufacturing System Resource Deployment

The result of cascading the strategic dimensions of market requirements through the planning matrices is a set of relevant and critical parameters of the physical resources or sub-systems of the manufacturing system that would fulfil the task and performance requirements of the manufacturing system. The parameters are grouped into categories that characterise each of the subsystems. Thus the output from the last phase of the methodology can be used as additional criteria for the selection of the most appropriate machines and equipment that match the critical resource requirements.

The overall scheme of the methodology is summed schematically in Figure 6.11. The arrows indicate the transformation from one phase to another. As can be seen from the diagram, the decisions on the selection of the resources in the manufacturing system can be traced back to the strategic objectives that had been established. Figure 6.12 shows the relationship between the strategic system function deployment with other decision domains in manufacturing system design. The conventional approach is to utilise information on product demands to define system requirements which is then followed by the selection of system elements, i.e., sequence 1-2-4. However, with the integration of the system function deployment, the strategic requirements of the business are considered concurrently as the product requirements. This is represented by the sequence 1, 2 and 3, followed by 4. Step 1 is necessary to define the processing sequence and hence the type of machines suitable for the part type. In step 3, issues related to the strategic requirements will be focused.

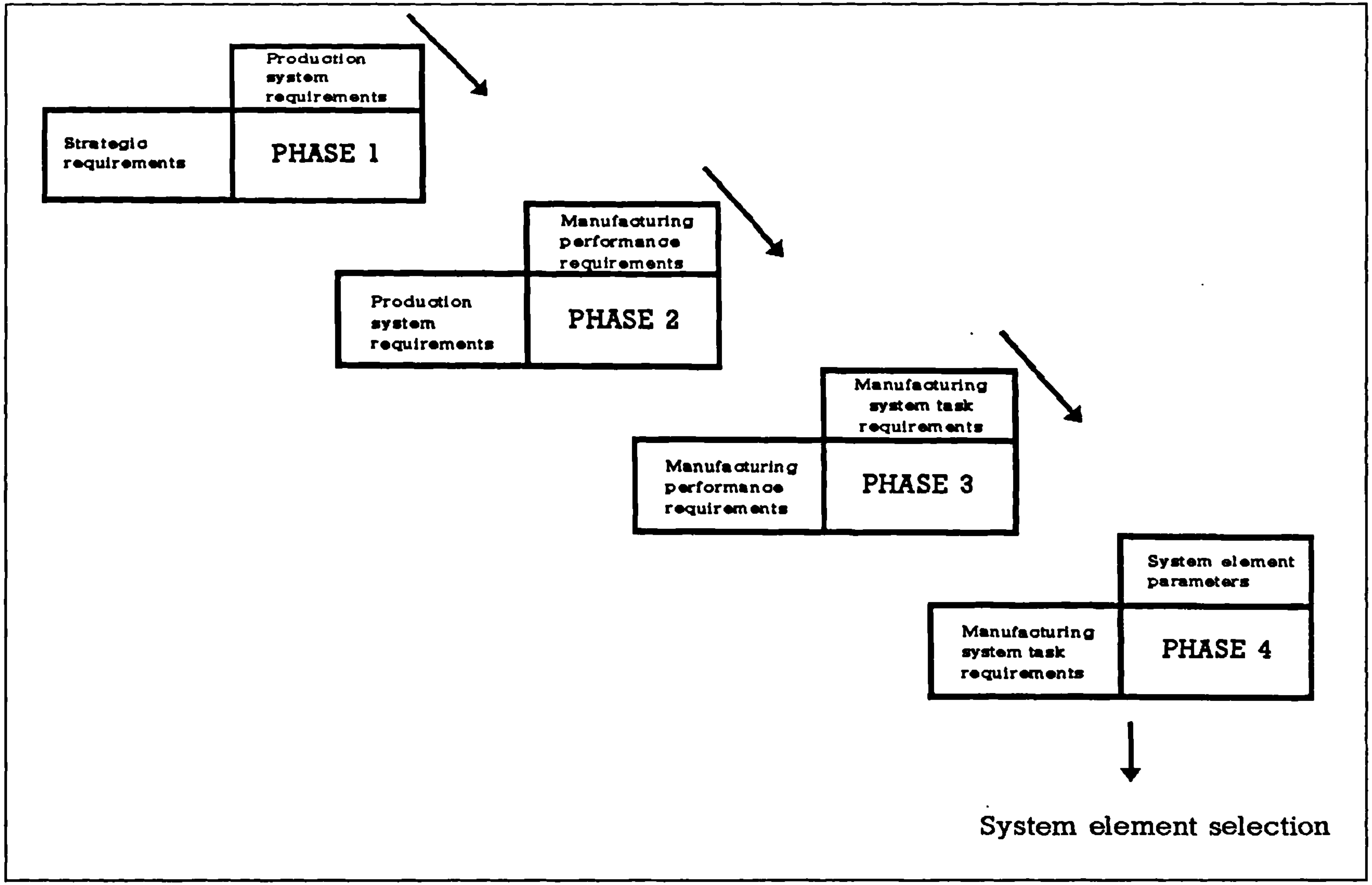


Figure 6.11 Strategic system function deployment.

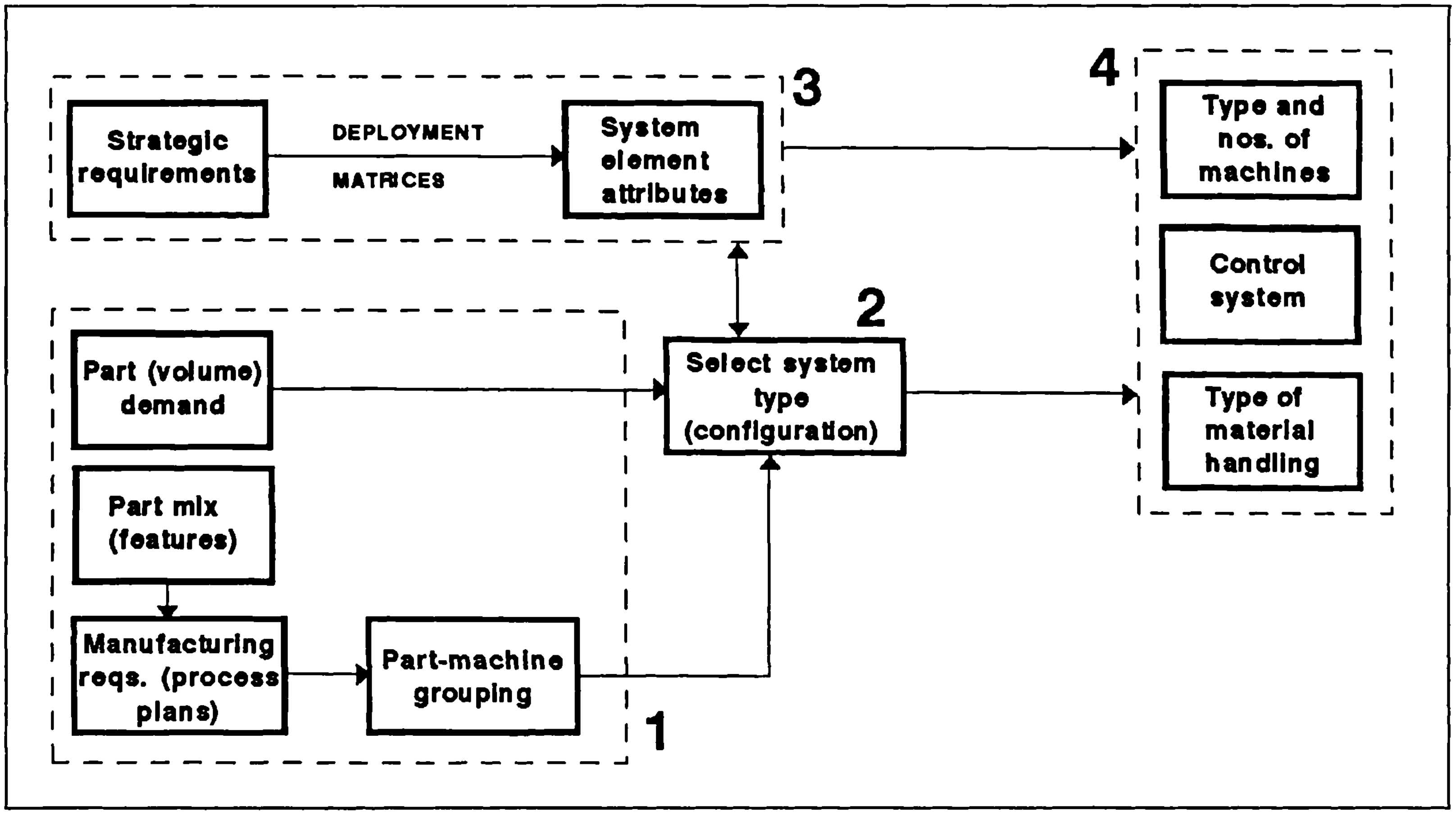


Figure 6.12 Strategic system function deployment within manufacturing system design.

The advantage of this approach is that both short and long term benefits will be gained. In the short term, the cost and delivery requirements will drive the design of efficient manufacturing system. Flexibility and quality requirements will ensure design consideration of effective and competitive manufacturing system that can react to the environment that is highly demanding in terms of quality and variability.

6.8 Summary

The chapter has outlined a systematic procedure for deploying the hierarchy of requirements in the proposed methodology for manufacturing system design. The deployment consists of four distinct phases and these are carried out using the planning matrices. Within each phase there are problem solving steps that involve both qualitative judgements and quantitative evaluations. The first phase translates the competitive priorities of the manufacturing strategy while the last phase relates the parameters of the manufacturing system. This systematic procedure of requirements deployment provides a means of integrating the short term and the long term requirements of manufacturing system design.

CHAPTER 7

INITIAL VERIFICATION OF THE METHODOLOGY

7.1 Introduction

Chapters 5 and 6 have detailed the philosophy and the theoretical framework for system function deployment methodology. The steps involved and the additional tool (AHP) employed have also been described. This chapter discusses the initial verification of the methodology using a few numerical examples. The objective of the examples is to investigate the viability and the limitations of the methodology in addressing the strategic objectives of a manufacturing organisation during the initial phases of manufacturing system design process. Specifically, the outcome of the systems requirements deployment, the effects of the degree of priorities of the strategic objectives, and the types of scale being used on the system element parameters will be investigated. Although the examples used are hypothetical in nature, they do however, sufficiently demonstrate the principles behind the proposed methodology. Since the objective is to illustrate the generic features of the strategic system function deployment methodology, the investigation is limited to the equipment selection problem of the manufacturing system design.

7.2 Assumptions

7.2.1 The System

With the above objectives in mind, certain assumptions about the type of system and the nature of products need to be made in order to make the implementation of the methodology tractable. The type of system to be used in the example is the flexible manufacturing cell in which families of parts can be produced. The reason this type of system is chosen is that, it is among the most widely used advanced manufacturing systems in industry, particularly by the small to medium sized companies which have limited investment funds. The higher percentage of manufacturers adopting this type of system has also been indicated by the result of the survey carried out at the initial stage of the research. Although relatively small in terms of size, as compared to the flexible manufacturing systems, a cell can have all the features of the full scale FMS. In addition, an FMC is generally considered as a feasible and economical approach to flexible automation in manufacturing [193, 252]. In order to reduce the complexity of the analysis, the cell is assumed to consist of a group of CNC machines sharing one common materials handling device. This description of the system is equivalent to the Flexible Manufacturing Cell (FMC) category of Maccarthy and Liu [168] and Kusiak [150]. The conceptual representation of the system is shown schematically in Figure 7.1.

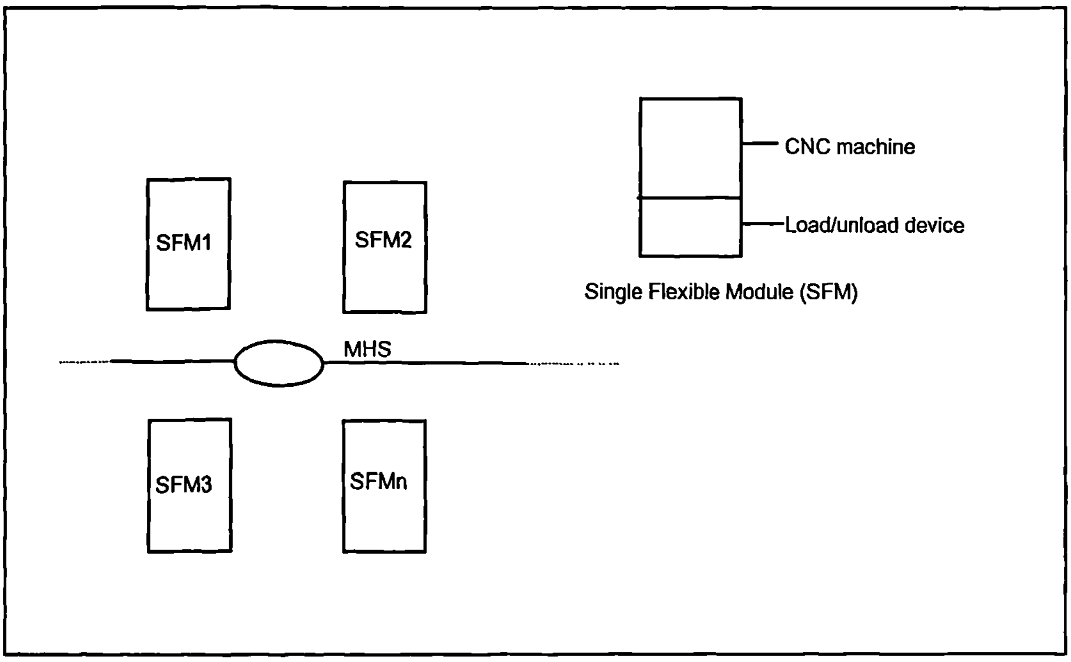


Figure 7.1 Schematic representation of the conceptual system.

An 'unmanned' cell is further assumed, where the role of human is only limited to programming and set-up, as well as preventive maintenance and repair. The cell contains CNC machines, workpiece/tool transfer device, load/unload device and cell controller. Such system has a high degree of flexibility and can react quickly to changes in product demand and design [26].

7.2.2 The Product

It was initially envisaged that a set of real products was to be used. However, it was found that such approach would require the actual involvement of a manufacturing company. The author found that it was not feasible to get the co-operation of companies, despite attempts made to contact a few manufacturing companies in the Merseyside. This is understandable as, a study on actual products would involve the need to get access to information such as design requirements, demand patterns, production quantities, quality levels, etc., which may be seen as sensitive.

A review of published literature also did not yield comparable studies which could be utilised. To overcome these limitations, the scope of verification had to be generic in nature and limited to simulated examples. Hence, the system to be tested is assumed to be based on a set of products that are suitable (in terms of the design requirements and the quantity) to be manufactured in the system. Such generality would necessarily preclude detail parameters such as the actual product design and the quantity to be produced. In addition the problem is also simplified as it is not necessary to consider the exact specifications of the equipment as well as the number of each equipment. These downstream decisions are not within the scope of the present research.

By adopting the flexible manufacturing cell, FMC, properties such as part volume and range of part type would fall within a stipulated range. This is based on the conventional representation of part variety-volume diagram, as shown in Figure 7.2. In addition, guidelines have also been provided on the basic part family that would be suitable for manufacturing within a cell as those parts that are made from metal bar stock up to 161 cm^2 (25 square inch) in cross section and having dimensional accuracy of ± 1.3 μm (0.05 inch) [58]. This basic family is representative of a large number of metal parts produced by machining operations today. With regard to the type of operations to be performed on the families of parts, it is assumed that the parts will require combinations of the typical operations performed in a machining facility such as turning, milling, drilling, reaming, taping and boring. These operations are available when suitable CNC lathes and machining centres are configured in the system.

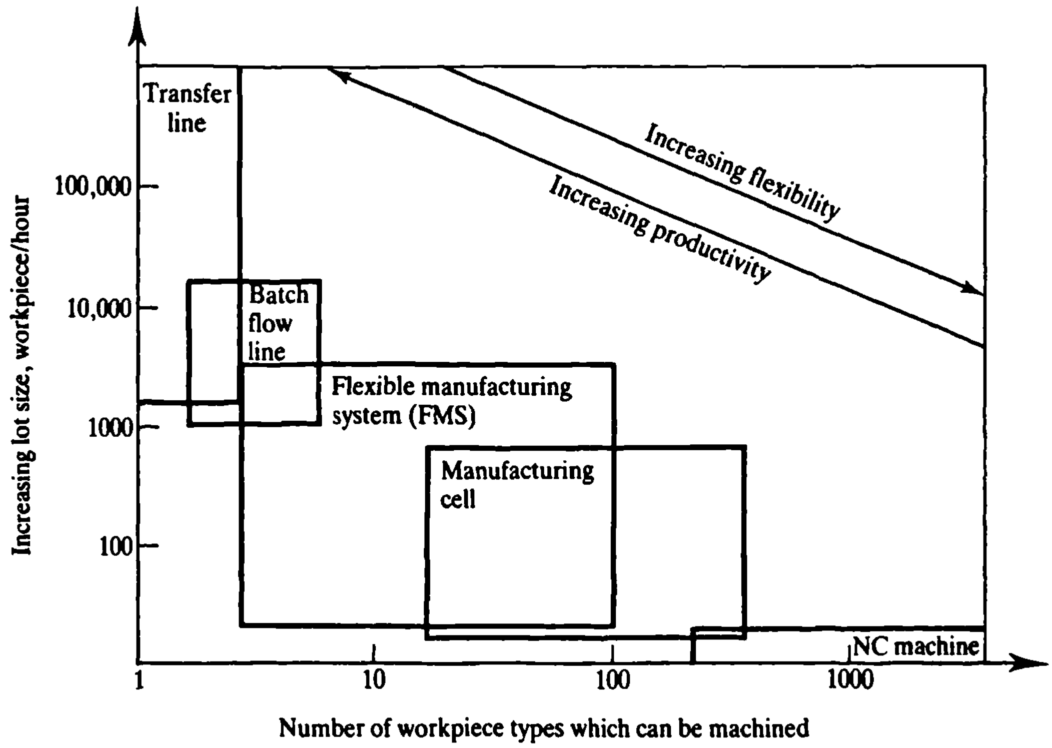


Figure 7.2 Modern manufacturing system concepts [218]

7.3 Implementation

7.3.1 Evaluation of Strategic Requirements Priorities

With 'meeting the competitive demand of the market' as the main objective or focus, the problem is decomposed into the next level which consists of the dimensions of market requirement or the competitive advantages. In order to arrive at the values of priority for each of the competitive advantages, the Analytic Hierarchy Process (AHP) is used partially at this stage. 'Partial,' because unlike the full AHP technique which has a complete hierarchy of objectives, criteria and alternatives, the use of the AHP in this part of the work will only involve the objective and criteria. Figure 7.3 illustrates schematically the six dimensions of market requirements that are necessary in meeting the corporate objective of surviving in the competitive market, as discussed in Chapter 5. However the questions to be answered are which dimensions satisfies the objective more, and how much more? To answer these questions a pairwise comparison of the dimensions is carried out via a matrix to arrive at the priority or relative importance values.

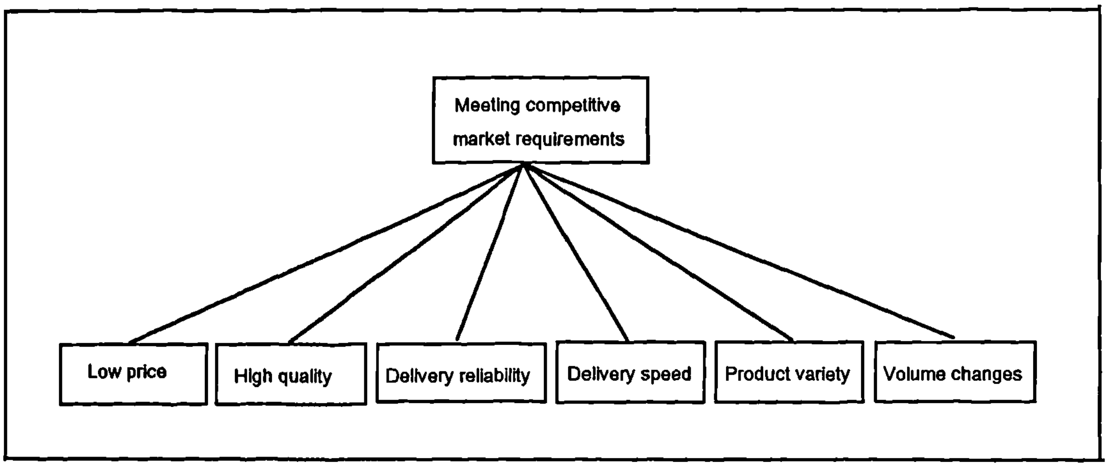


Figure 7.3 Decomposition of market requirements

Pairwise Comparison

In the pairwise comparison the competitive advantages of the strategic requirements are compared to each other. The pairwise comparison matrix is set-up and the priority vector evaluated. The dimension or criterion with the highest priority value will be construed as having the greatest degree of importance in influencing the strategic objectives and vice-versa. This procedure is summarised in Table 7.1.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	D_1/D_2	D_1/D_3	D_1/D_4	D_1/D_5	D_1/D_6		
High quality, D_2		1	D_2/D_3	D_2/D_4	D_2/D_5	D_2/D_6		
Delivery reliability, D_3			1	D_3/D_4	D_3/D_5	D_3/D_6		
Delivery speed, D_4				1	D_4/D_5	D_4/D_6		
Product variety, D_5					1	D_5/D_6		
Volume changes, D_6						1		

Table 7.1 Format of pairwise comparison matrix.

In Table 7.1, D_i/D_j indicates the degree of preference or importance of one dimension, D_i, over another dimension, D_j. Below the diagonal are values of the reciprocal of the entries above it. The priority values are expressed in percentages. Detail discussion of the matrix calculations is provided in Appendix G. The last column contains the consistency ratio (CR) which indicates whether the decision in assigning the values for D_i/D_j has been consistent. It has been established that a value of CR which is less than 0.1 (10%) indicates that the decisions are consistent [224]. Once the values and the consistencies of the priority are established, they are entered into the WHYs column of the planning matrix. Tables 7.2 to 7.11 show the values of the priority for the competitive advantages obtained, based on the calculation for a few simulated cases. For cases #1 - #4, the various values for the pairwise comparison were randomly chosen. For cases #5 - #6, the values were selected such that a particular emphasis was given to each of the strategic requirements.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	5	1/3	1/5	3	2	17.2	
High quality, D_2	1/5	1	1	1/6	1/2	1	6.4	
Delivery reliability, D_3	3	1	1	1/3	1/3	1/3	9.4	0.41
Delivery speed, D_4	5	6	3	1	3	1/3	27.7	
Product variety, D_5	1/3	2	3	1/3	1	4	21.8	
Volume changes, D_6	1/2	1	3	3	1/4	1	17.8	

Table 7.2 Case #1.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1/5	3	5	1/3	1/2	16.7	
High quality, D_2	5	1	1	6	2	1	24.8	
Delivery reliability, D_3	1/3	1	1	3	3	3	20.7	0.41
Delivery speed, D_4	1/5	1/6	1/3	1	1/3	3	9.1	
Product variety, D_5	3	1/2	1/3	3	1	1/4	12.2	
Volume changes, D_6	2	1	1/3	1/3	4	1	16.6	

Table 7.3 Case #2.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1	7	7	5	5	36	
High quality, D_2	1	1	5	5	3	3	28	
Delivery reliability, D_3	1/7	1/5	1	3	5	7	16	0.22
Delivery speed, D_4	1/7	1/5	1/3	1	3	3	8	
Product variety, D_5	1/5	1/3	1/5	1/3	1	5	8	
Volume changes, D_6	1/5	1/3	1/7	1/3	1/5	1	5	

Table 7.4 Case #3

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	5	7	9	9	7	53.2	
High quality, D_2	1/5	1	3	3	2	1	13.8	
Delivery reliability, D_3	1/7	1/3	1	3	5	3	13.6	0.15
Delivery speed, D_4	1/9	1/3	1/3	1	1	3	7.3	
Product variety, D_5	1/9	1/2	1/5	1	1	1/3	4.5	
Volume changes, D_6	1/7	1	1/3	1/3	3	1	7.7	

Table 7.5 Case #4.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	5	7	9	9	7	56.0	
High quality, D_2	1/5	1	3	3	2	1	14.1	
Delivery reliability, D_3	1/7	1/3	1	2	3	2	10.9	0.045
Delivery speed, D_4	1/9	1/3	1/2	1	1	2/3	5.3	
Product variety, D_5	1/9	1/2	1/3	1	1	2/3	5.4	
Volume changes, D_6	1/7	1	1/2	3/2	3/2	1	8.3	

Table 7.6 Case #5.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1/9	1/7	1/3	3	1/4	5.3	
High quality, D_2	9	1	5	7	7	5	49.5	
Delivery reliability, D_3	7	1/5	1	5	5	3	23.8	0.08
Delivery speed, D_4	3	1/7	1/5	1	1	1/3	6.4	
Product variety, D_5	1/3	1/7	1/5	1	1	1/4	4.4	
Volume changes, D_6	4	1/5	1/3	1/3	4	1	10.6	

Table 7.7 Case #6.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1/2	1/7	1/5	1/3	1/2	4.5	
High quality, D_2	2	1	1/5	1/5	1/2	1	7.5	
Delivery reliability, D_3	7	5	1	3	5	3	42.0	0.03
Delivery speed, D_4	5	5	1/3	1	3	3	25.6	
Product variety, D_5	3	2	1/5	1/3	1	1	10.7	
Volume changes, D_6	2	1	1/3	1/3	1	1	9.7	

Table 7.8 Case #7.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1/2	4	2/7	3	7	20	
High quality, D_2	2	1	3/2	1/3	5	3	19	
Delivery reliability, D_3	1/4	2/3	1	1/5	2	1/3	7	0.07
Delivery speed, D_4	7/2	3	5	1	6	4	39	
Product variety, D_5	1/3	1/5	1/2	1/6	1	4/6	5	
Volume changes, D_6	1/7	1/3	3	1/4	6/4	1	9	

Table 7.9 Case #8.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1	2/7	2/5	1/9	1/7	4.4	
High quality, D_2	1	1	2/3	2	1/5	1/3	8.4	
Delivery reliability, D_3	7/2	3/2	1	3	1/3	1/5	12.8	0.03
Delivery speed, D_4	5/2	1/2	1/3	1	1/5	1/3	7.0	
Product variety, D_5	9	5	3	5	1	5/3	38.2	
Volume changes, D_6	7	3	5	3	3/5	1	29.2	

Table 7.10 Case #9.

Dimensions of market requirements	D_1	D_2	D_3	D_4	D_5	D_6	Priority	Consistency Ratio (CR)
Low price, D_1	1	1/2	1/3	1/3	1/4	1/8	4	
High quality, D_2	2	1	1/3	1/3	1/2	1/5	7	
Delivery reliability, D_3	3	3	1	2	1	1/3	16	0.06
Delivery speed, D_4	3	3	1/2	1	1/5	1/7	10	
Product variety, D_5	4	2	1	5	1	1/3	19	
Volume changes, D_6	8	5	3	7	3	1	44	

Table 7.11 Case #10.

7.3.2 Requirements Deployment

The deployment of the strategic requirements is carried out through a series of planning matrices. The decomposition of the requirements from strategic to the lower levels of the requirements hierarchy has been described in Chapter 5 (Sections 5.8.3-5.8.4). Assumptions need to be made with regards to the strength of the relationships between the WHATs and the HOWs in the planning matrices. The values in the examples are arbitrarily chosen in order to illustrate the principles behind the methodology. These are shown in Figures 7.4 - 7.7. Again the actual values in practice can be obtained through various methods such as crossfunctional team efforts, and can vary from one manufacturing set-up to another.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

	Production System Requirements	Design and engineering cost	Purchasing cost	Marketing and sales cost	Administrative cost	Manufacturing cost	System procurement cost	Design and engineering quality	Purchasing quality	Manufacturing quality	Marketing and sales quality	Production flexibility	Market flexibility	Design and development lead time	Purchasing lead time	Manufacturing lead time	Distribution lead time
Competitive priorities																	
Low price		●	△	○	△	●	△	○	△	●		○	○	△		○	
High quality		●	△			●	○	●	●	●	△	○		○		○	
Delivery reliability		○				●	○	○	○	○	●	●	●	●	●	●	●
Delivery speed		○	○	○		○		○	○	○	○	●	●	●	●	●	●
Product variety		●	△	○		●	○	●	△	●		●	●			○	
Volume changes			○		△	○				○		●	●			●	

RELpm1 (WHATs–HOWs relationships for PM1)

Figure 7.4 An example of WHATs - HOWs relationships for Planning Matrix 1.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

	Manufacturing System Performance Requirements	Processing cost	Manufacturing overheads	Percentage rejects	Rework	Warranty cost	System reliability	System throughput	Non-operation time	System utilization	Volume flexibility	Process flexibility	Product flexibility	Routing flexibility	Expansion flexibility
Production System Requirements															
Manufacturing cost		●	●	●	●	△	○	○	○	○	○	●	●	○	△
Manufacturing quality		○	●	●	●	●	●	△		○	○	○	○	○	
Production flexibility		●	●	△	△	○	●	●	○	●	●	●	●	●	●
Market flexibility		○	●				●			●	●	●	●	●	●
Manufacturing lead time		○	●	○	○		●	●	●	●	○	○	○	○	

RELpm2 (WHATs–HOWs relationships for PM2)

Figure 7.5 An example of WHATs - HOWs relationships for Planning Matrix 2

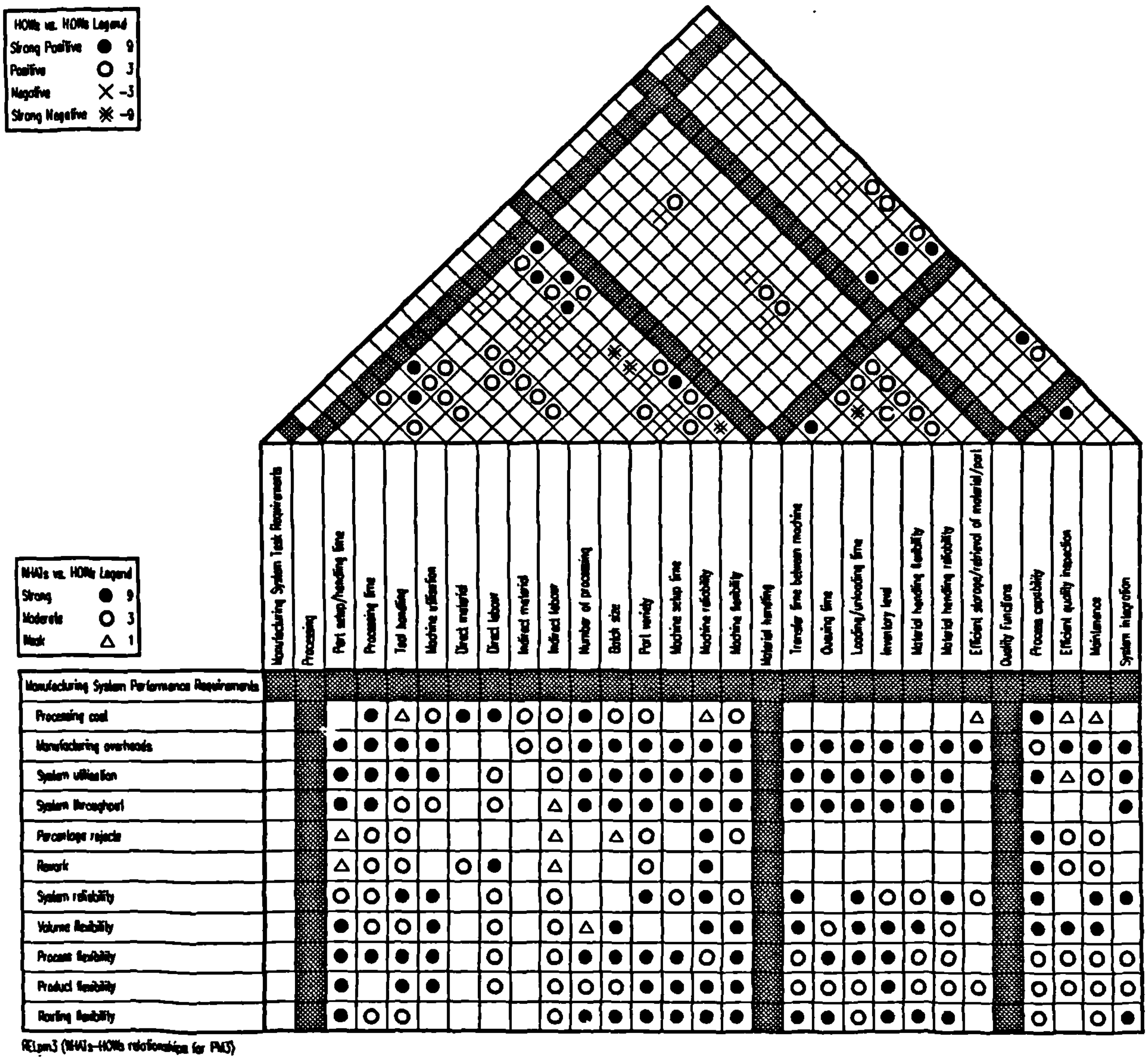


Figure 7.6 An example of WHATs - HOWs relationships for Planning Matrix 3.

WHATs vs. HOWs Legend

Strong ● 9

Moderate ○ 3

Weak △ 1

Manufacturing System Task Requirements	System element attributes	Machining centre	Precision parameters	Table and pallet parameters	Machining and spindle	Automatic tool change	Monitoring system	CNC software	CNC Lathe	Precision parameters	Turning parameters	Spindle parameters	Tooling	Monitoring system	CNC software	Transportation	Transport parameters	Load parameters	Transport software	Space requirements	Loading/unloading.	Loading parameters	Dynamic parameters	Accuracy	Controller	System controller	Structure	Compatibility	Production planning and control
Processing																													
Setup time/Part handling			●	●				○		●					○							○	●	●	○			●	△
Processing time			○	○	●	○	○	○		○	●	●	○	○	○													○	
Tool handling						●		●					●		●								○	○	○		●	○	
Machine utilisation				●	●	●	●	●			●	●	●	●	●		●		○			○	○		○		○	●	●
Number of processing				○	○	●	●	●			○	○	●	●	●		●		○			○	○	○	○		●	○	●
Batch size					○	○	○				○	○	○	○			●	○	○			○			○		○		○
Part variety			●	●	●	●	●	●		●	●	●	●	●	●		●	●	●			●	●	○	●		●	○	●
Machine set-up time			●	○	●	●	○	○		●	●	●	●	○	○													○	△
Machine reliability			●		●	○	●	○		●	●	●	●	●	○														
Machine flexibility				●	●	●	●	●			●	●	●	●	●		○		○			○	△	○	○		○	●	●
Material handling																													
Transfer time between machine																	●		●			○	○				●	●	○
Queueing time					○	●		○			○	○	●		○		●		●			●	●		●		△	●	●
Loading/unloading time								○							○				○			●	●	△	●		○	●	△
Inventory level					○	○		○			○	○	○		○		●		●			●	△		●		●	●	●
Material handling flexibility																	●	●	●	○		●	○		●		○	○	○
Material handling reliability																	●	○	●	△		●	●	●	●		△	●	○
Quality Functions																													
Process capability			●		●	○	●	○		●	●	●	○	●	○												○	○	
Maintenance							●							●						●							○		
System integration						○	○	●					○	○	●		●		●			●			●		●	●	●

RELpm4 (WHATs-HOWs relationships for PM4)

Figure 7.7 An example of WHATs - HOWs relationships for Planning Matrix 4.

Based on the given relationships between the WHATs and the HOWs, and taking into account the degree of importance of the WHATs for each of the planning matrices, the requirements are then deployed down the hierarchy. The detail description of the requirements deployment was given in Chapter 6. Case #5 is chosen to illustrate the typical results which might be obtained, and these are shown in Figures 7.8 (a-d).

As explained in Chapter 6, the context of the analysis is that of manufacturing system. Referring to Planing Matrix #1 (Figure 7.8a), the HOWs that are carried to the next phase are only those that are directly related to manufacturing system. Thus, cost and quality aspects that are related to design, purchasing cost and other functions within the production system that are not manufacturing related and manufacturing specific are not deployed further. The selection of the HOWs for further translation is based on the priority set by the criteria included in the HOW MUCHes room. In the examples, only three variables are considered: absolute importance, relative importance, and rank. These are defined as follows:

Absolute importance = $\sum$ (Degree of priority of each WHAT) * (Strength of relationship between the WHATs and the HOWs),

Relative importance = Value of absolute importance for each HOW/Total values of absolute importance, and

$$\text{Rank} = \frac{\text{Value of relative importance for a HOW} * 5}{\text{Maximum value of relative importance}}.$$

The value of 5 in the above equation signifies that a linear scale of 5-4-3-2-1 is being used, where 5 represents the most important option and 1 the least important. Thus in Figure 7.8a, for manufacturing cost and manufacturing lead time, the ranks are 5 {(17/17)* 5}, and 3 {(9/17)*5} respectively. The need to introduce rank at this stage is necessary as not all of the HOWs are deployed, whereas the values for the absolute importance and the relative importance are calculated for all the options. Rank value is used as it gives more meaningful degree of relative importance of the HOWs, as compared to mere percentages of the relative importance. Once selected, the HOWs are entered as the WHATs (or requirements) to the next planning matrix. The respective values of the rank are carried to the WHYs room, which serve as a measure of relative importance. The same procedure is performed for other planning matrices.

In Figure 7.8d, the values of the ranking for the parameter groups are evaluated. Each parameter group represents a set of technical features or characteristics of the manufacturing system elements.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

Production System Requirements	Design and engineering cost	Purchasing cost	Marketing and sales cost	Administrative cost	Manufacturing cost	System procurement cost	Design and engineering quality	Purchasing quality	Manufacturing quality	Marketing and sales quality	Production flexibility	Market flexibility	Design and development lead time	Purchasing lead time	Manufacturing lead time	Distribution lead time	Degree of priority
Competitive priorities																	
Low price	●	△	○	△	●	△	○	△	●		○	○	△		○		56
High quality	●	△			●	○	●	●	●	△	○		○		○		14
Delivery reliability	○				●	○	○	○	○	●	●	●	●	●	●	●	11
Delivery speed	○	○	○		○		○	○	○	○	●	●	●	●	●	●	5
Product variety	●	△	○		●	○	●	△	●		●	●			○		5
Volume changes		○		△	○				○		●	●			●		8
Direction of improvements	↓	↓	↓	↓	↓	↓	↑	↓	↑	↑	↑	↑	↓	↓	↓	↓	
Absolute importance	723	114	198	64	813	146	387	235	747	128	471	429	242	144	441	144	
Relative importance	13	2	4	1	15	3	7	4	14	2	9	8	4	3	8	3	
Rank	4				5				5		3	3			3		

cs5pm1

Figure 7.8a Strategic requirements deployment for Case #5.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

Manuf System Performance Reqts	Processing cost	Manufacturing overheads	Percentage rejects	Rework	Warranty cost	System reliability	System throughput	Non-operation time	System utilization	Volume flexibility	Process flexibility	Product flexibility	Routing flexibility	Expansion flexibility	Relative importance
Production System Requirements															
Manufacturing cost	●	●	●	●	△	○	○	○	○	○	●	●	○	△	5
Manufacturing quality	○	●	●	●	●	●	△		○	○	○	○	○		5
Production flexibility	●	●	△	△	○	●	●	○	●	●	●	●	●	●	3
Market flexibility	○	●				●			●	●	●	●	●	●	3
Manufacturing lead time	○	●	○	○		●	●	●	●	●	●	●	●		3
Direction of improvements	↓	↓	↓	↓	↓	↑	↑	↓	↑	↑	↑	↑	↑	↑	
Absolute importance	105	171	102	102	59	141	74	51	111	111	141	141	111	59	
Relative importance	7	12	7	7	4	10	5	3	8	8	10	10	8	4	
Ranks	3	5	3	3	2	4	2	1	3	3	4	4	3	2	

cs5PM2

Figure 7.8b Production system requirements deployment for Case #5.

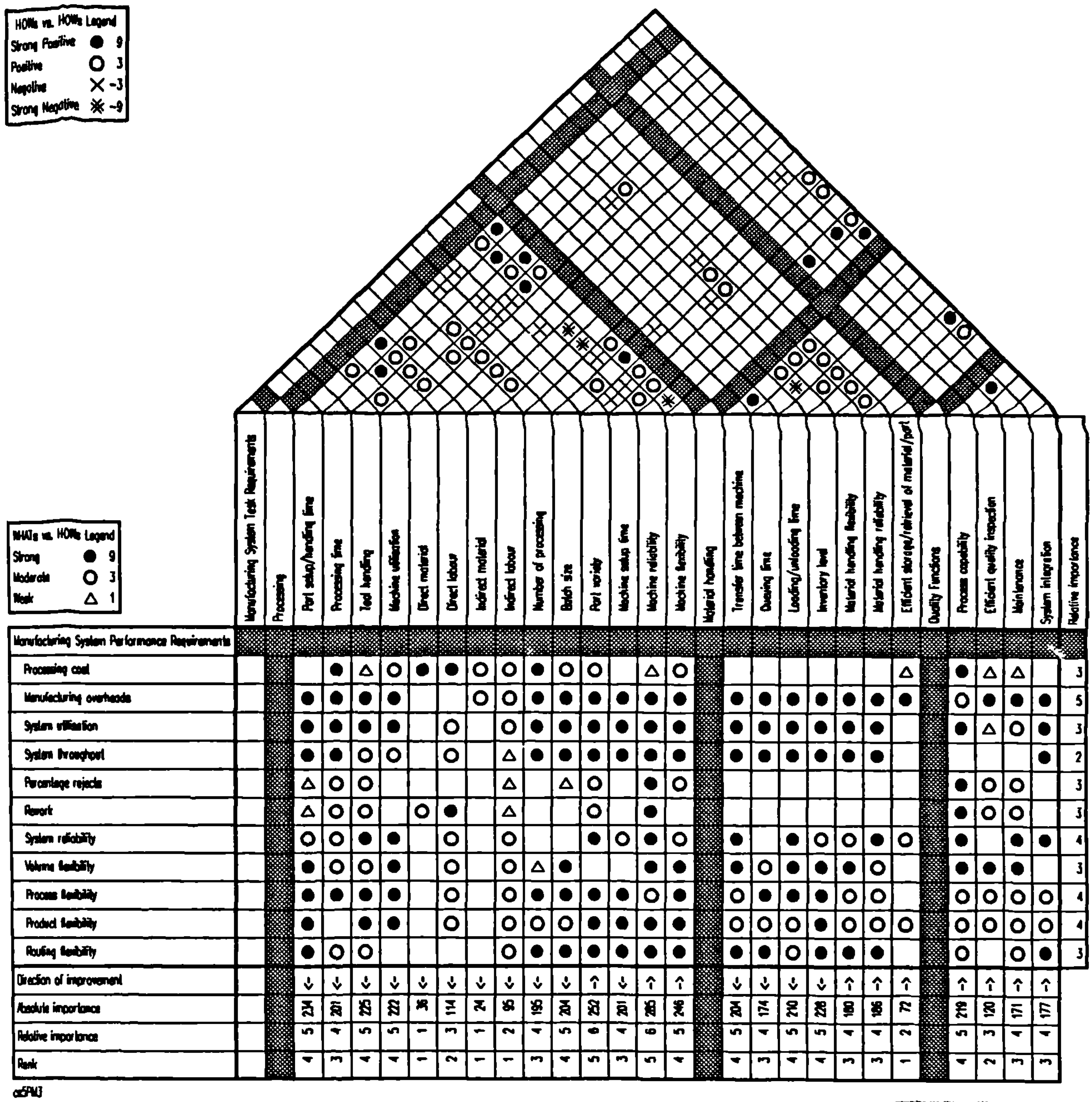


Figure 7.8c Manufacturing system performance requirements deployment for Case #5.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

Manufacturing System Task Requirements	System element attributes	Machining centre	Precision parameters	Table and pallet parameters	Machining and spindle	Automatic tool change	Monitoring system	CNC software	CNC Lathe	Precision parameters	Turning parameters	Spindle parameters	Tooling	Monitoring system	CNC software	Transportation	Transport parameters	Load parameters	Transport software	Space requirements	Loading/unloading	Loading parameters	Dynamic parameters	Accuracy	Controller	System controller	Structure	Compatibility	Production planning and control	Relative importance
Processing																														
Setup time/Part handling			●	●				○		●				△	○							○	●	●	○			●	△	4
Processing time			○	○	●	○	○	○		○	●	●	○	○	○													○		3
Tool handling						●	△	●					●	△	●								○	○	○		●	○		4
Machine utilisation				●	●	●	●	●			●	●	●	●	●		●		○			○	○		○		○	●	●	4
Number of processing				○	○	●	●	●			○	○	●	●	●		●		○			○	○	○	○		●	○	●	3
Batch size					○	○	○				○	○	○	○			●	○	○			○			○		○		○	4
Part variety			●	●	●	●	●	●		●	●	●	●	●	●		●	●	●			●	●	○	●		●	○	●	5
Machine set-up time			●	○	●	●	○	○		●	●	●	●	○	○													○	△	3
Machine reliability			●		●	○	●	○		●	●	●	●	●	○															5
Machine flexibility				●	●	●	●	●			●	●	●	●	●		○		○			○	△	○	○		○	●	●	4
Material handling																														
Transfer time between machine																	●		●			○	○				●	●	○	4
Queuing time					○	●		○			○	○	●		○		●		●			●	●		●		△	●	●	3
Loading/unloading time								○							○				○			●	●	△	●		○	●	△	4
Inventory level					○	○		○			○	○	○		○		●		●			●	△		●		●	●	●	4
Material handling flexibility																	●	●	●	○		●	○		●		○	○	○	3
Material handling reliability																	●	○	●	△		●	●	●	●		△	●	○	3
Quality Functions																														
Process capability			●		●	○	●	○		●	●	●	○	●	○												○	○		4
Maintenance							●							●						●							○			3
System integration					○	○	○	●					○	○	●		●		●			●			●		●	●	●	3
Absolute importance			198	180	303	303	295	297		198	294	294	333	299	297		336	93	282	39		294	233	115	294		291	372	287	
Relative importance			3	3	5	5	5	5		3	5	5	6	5	5		6	2	5	1		5	4	2	5		5	6	5	
Rank			2	2	4	4	4	4		2	4	4	5	4	4		5	1	4	1		4	3	1	4		4	5	4	

c5qm4

Figure 7.8d Manufacturing system task requirements deployment for Case #5.

7.4 Variations in Requirements Deployment

7.4.1 Effect of Changing the Strategic Focus

Depending on the market environment in which a manufacturing organisation is operating, the emphasis on the strategic requirements may vary. Tests were carried out to verify the effect of changing the priority of the competitive advantages. The output from the priority evaluation for cases #5 to #10 in Section 7.3 (Tables 7.2 - 7.11), where decisions have been consistent, is summarised and presented in the form of the bar graph, as shown in Figure 7.9. Based on the values of the relative importance calculated through the use of pairwise comparison, as shown in Figure 7.9, deployments were carried out for those case examples. The bar graphs in Figure 7.10(a-d) show the resulting ranks on the requirements at each level of the hierarchy (a-c) and the parameter groups of the system element (d).

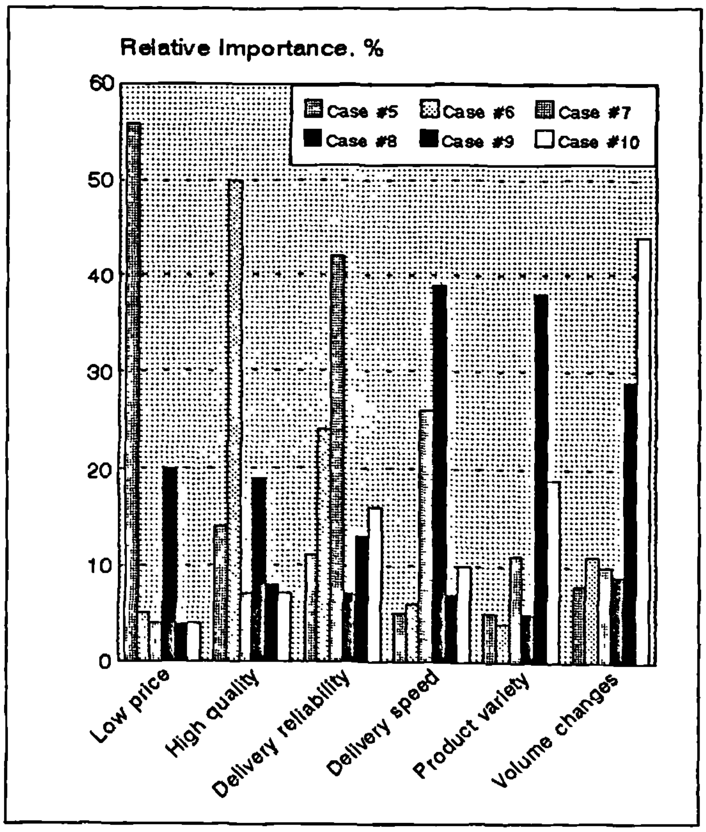


Figure 7.9 Degree of priorities for strategic requirements (in %).

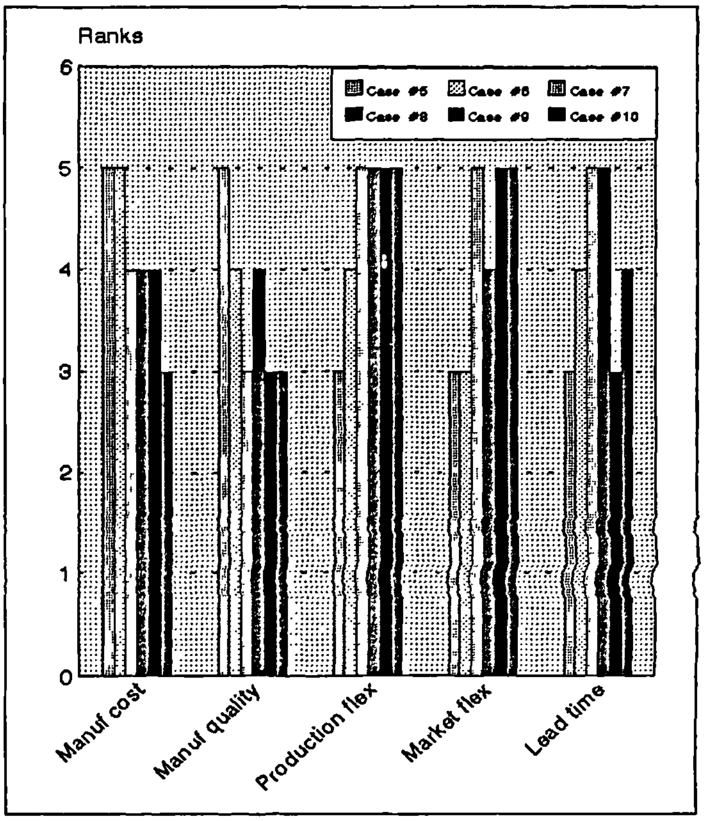


Figure 7.10a Production system requirements

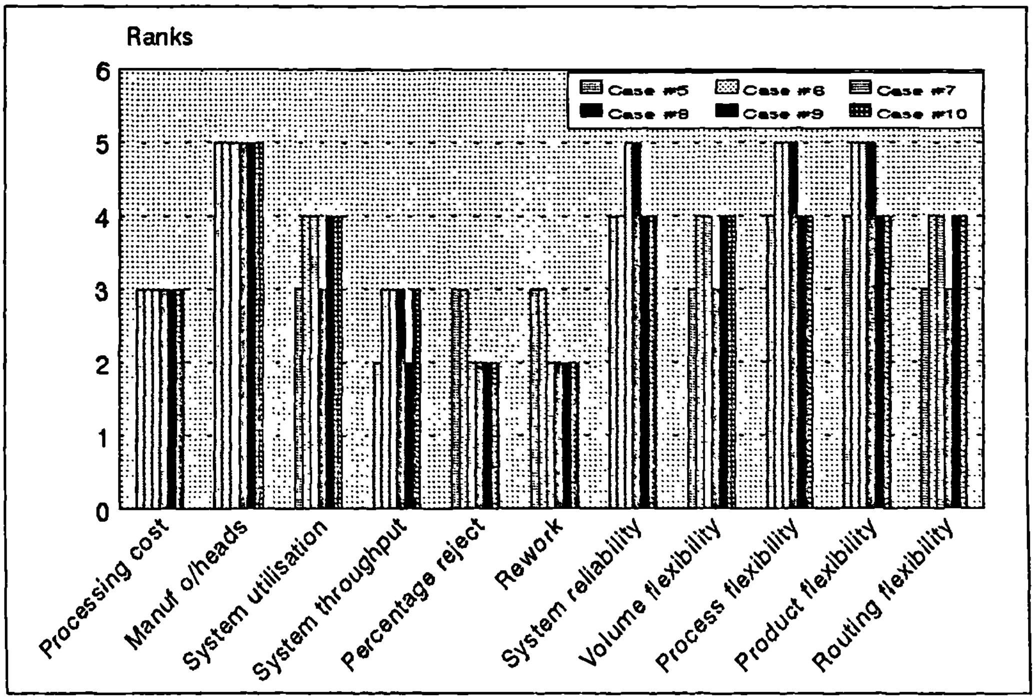


Figure 7.10b Ranking for manufacturing system performance requirements.

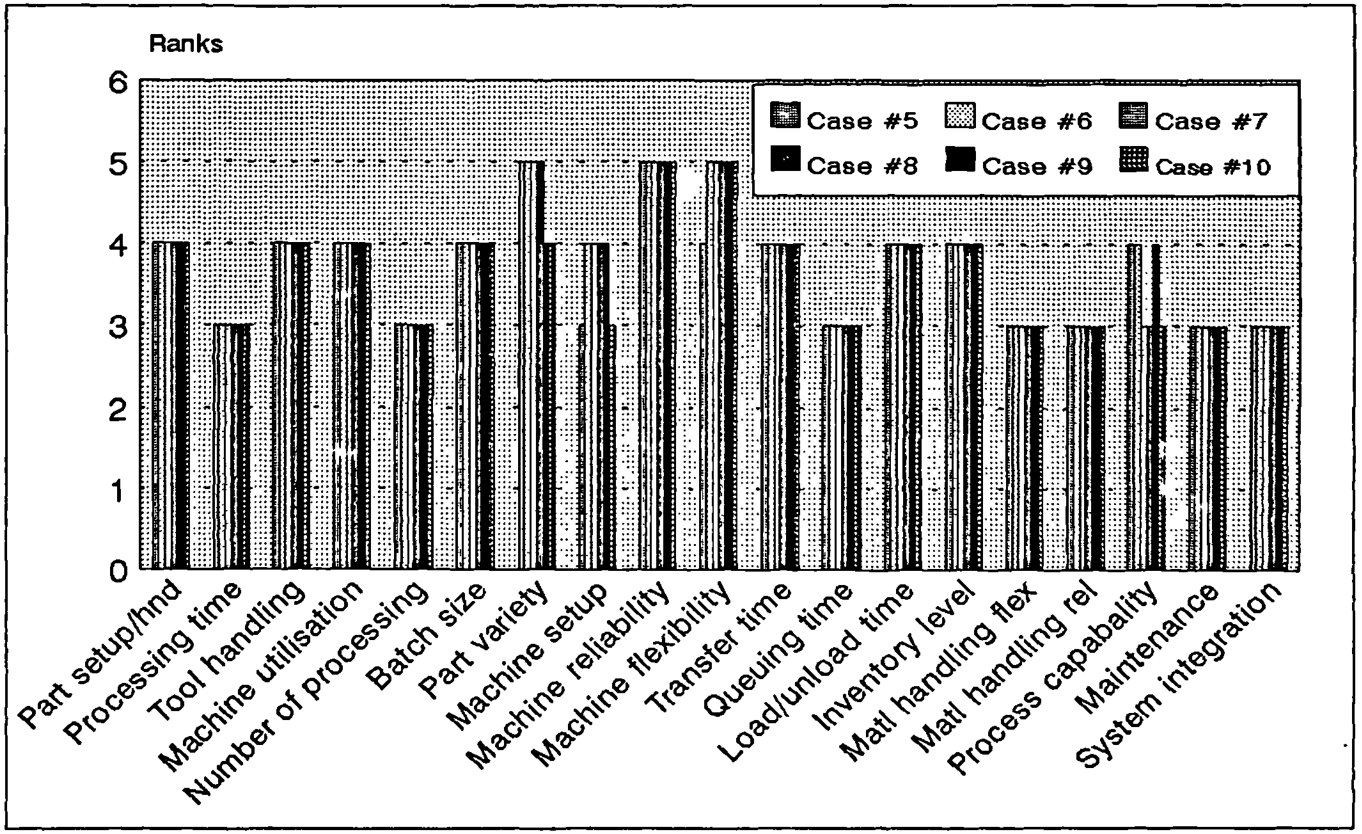


Figure 7.10c Ranking for manufacturing system task requirements.

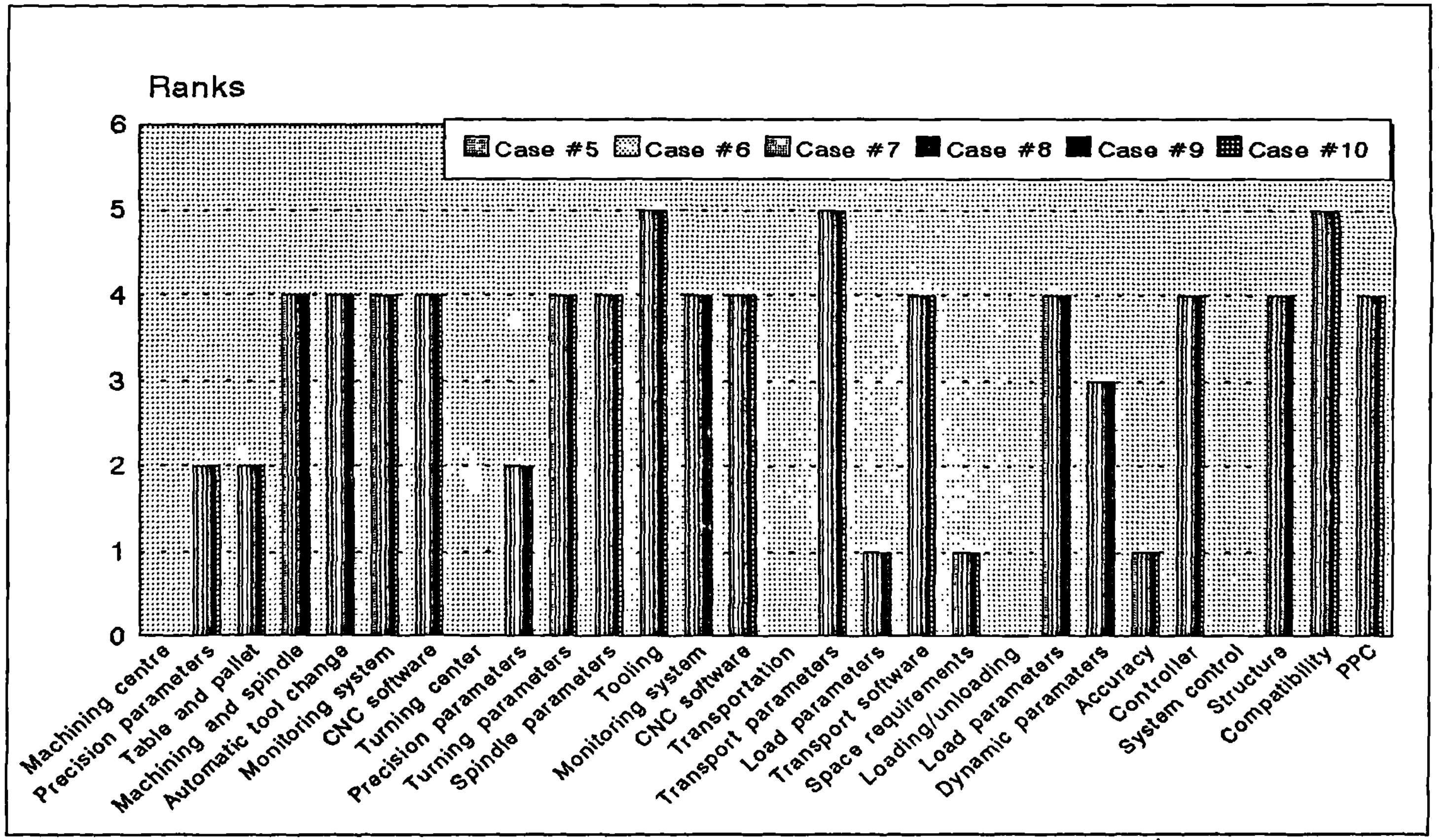


Figure 7.10d Ranking for parameter groups of the system elements.

7.4.2 Effects of Using Different Ranking Scales

A geometric scale was introduced to rank the relative importance of the HOWs in the planning matrices. The objective was to see whether there was any significant difference in the final ranking of the parameter groups. It was anticipated that the bigger margins between each number in the geometric scale would provide prominent differences in the values of the ranking. This was achieved by converting the current linear scale used in each of the planning matrices into the equivalent geometric scale. Two forms of conversion were used, as shown in Table 7.12.

<table>
<tr><td>Linear scale</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td></tr>
<tr><td>Geometric scale</td><td colspan="2">9</td><td>3</td><td colspan="2">1</td></tr>
</table>

'A'

<table>
<tr><td>Linear scale</td><td>5</td><td>4</td><td>3</td><td>2</td><td>1</td></tr>
<tr><td>Geometric scale</td><td>9</td><td colspan="2">3</td><td colspan="2">1</td></tr>
</table>

'B'

Table 7.12 Linear-Geometric Scale Conversion.

Tests were carried out on Cases 5-10, and the results for the ranking of the parameter groups in planning matrix #4 are summarised in Figure 7.11.

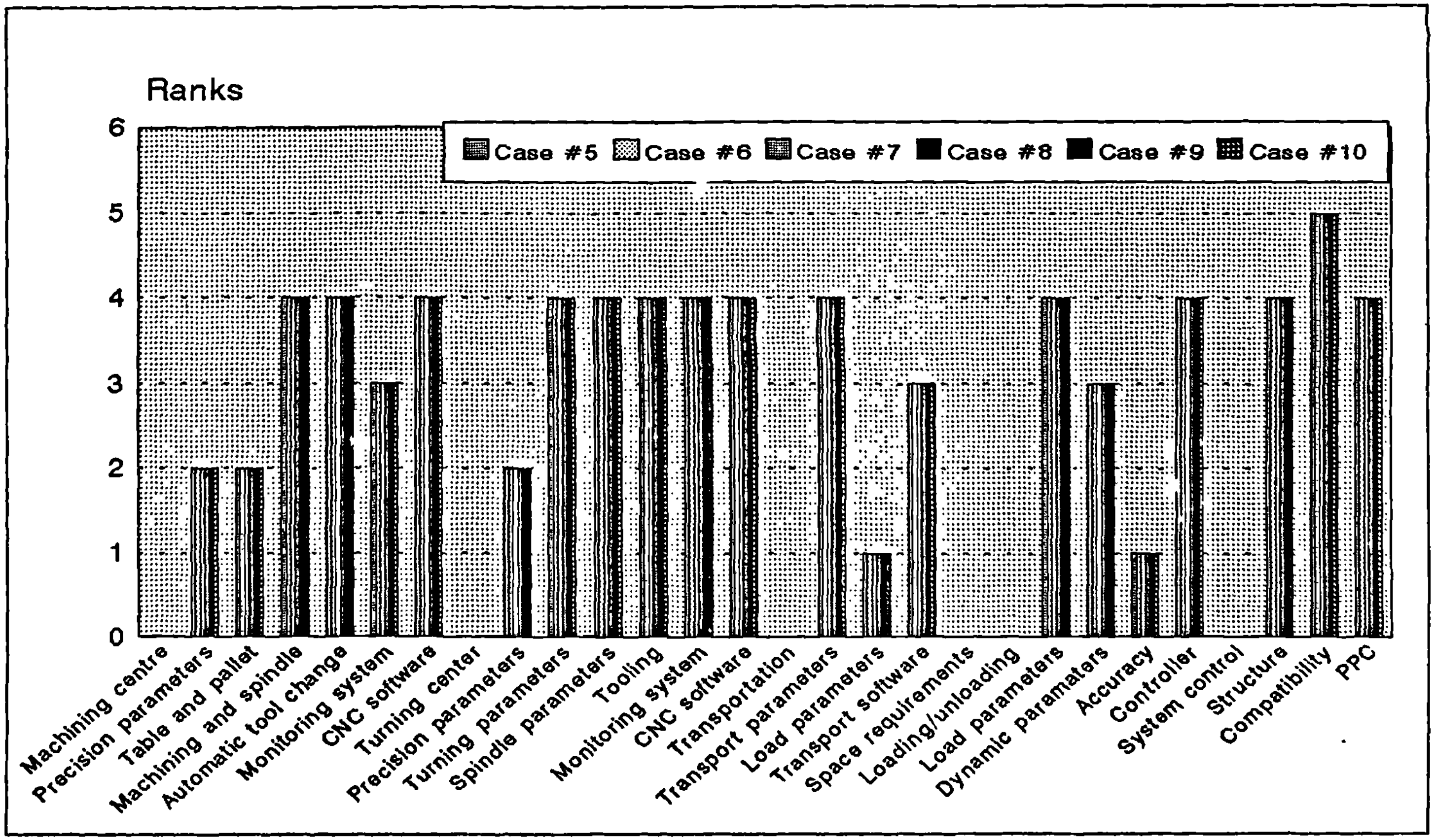


Figure 7.11a Effect of changing the ranking scale (Geometric 'A')

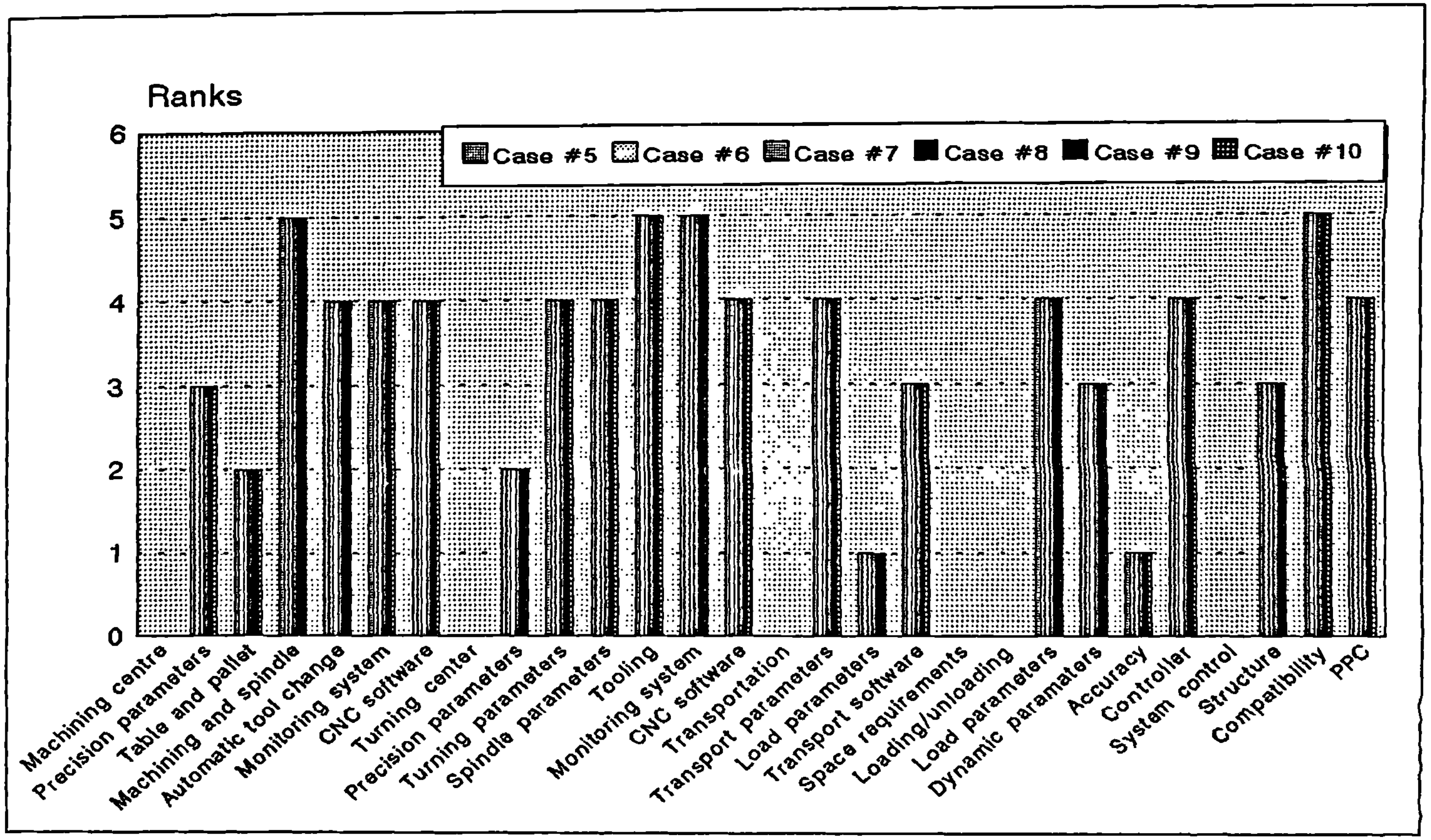


Figure 7.11b Effect of changing the ranking scale (Geometric 'B')

7.4.3 Effects of Introducing Consolidation Factoring

The Consolidation Factoring (CF) was first introduced as a method of improving the QFD process when applied to the general business decisions involving multiple option or selection [281]. This is achieved by allocating credit to decision options (HOWs) in proportion to how each option addresses all specified criteria (WHATs) in conjunction with the total weighted relationships (WHATs - HOWs relationships). The value of CF can be between 1 - 2.

In the present work, the CF is used to see *if* it can improve the distinction among the parameter groups in the fourth planning matrix. An example for Case #5 (using the linear scale for rank) is presented in Figure 7.12 to illustrate the use of CF for planning 4. In the planning matrix, all the rows and columns are numbered (a feature available in QFD/CAPTURE). Rows 1-3 in the HOW MUCHes room provide information on the normal evaluation of the ranking. The maximum total possible (Row 5) refers to the maximum value of the WHATs-HOWs relationships, i.e., sum of the values of relative importance in the WHYs column multiplied by 9. In the example, this value is 630 (70*9), which is the same for all the columns.

Row 6 lists for each column the value obtained by dividing the absolute importance in Row 1 by 630. For example, in column 3, the value is 0.3 (198/630). Row 7 evaluates the ratio of the number of demands actually addressed and the maximum number possible, which is 19 (rows 3-12, 14-19, 21-23). Hence for column 3, the value is 0.3 (6/19). In Row 8, consolidation factoring, CF = 1 + (0.3*0.3) = 1.1 (1.09). The revised absolute importance is obtained by multiplying the absolute importance in Row 1 of the HOW MUCHes room with the CF, i.e., 198*1.1 = 218. The values of the revised relative importance and the new ranking are evaluated as before. Figure 7.13 shows the distribution of the ranking for the parameter groups using the CF.

Figure 7.14 compares the effects of using the different scales and the CF on the values of the ranking for the parameter groups for Case #6.

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	△	1

		System element attributes	Machining centre	Precision parameters	Table and pallet parameters	Machining and spindle	Automatic tool change	Monitoring system	CNC software	CNC Lathe	Precision parameters	Turning parameters	Spindle parameters	Tooling	Monitoring system	CNC software	Transportation	Transport parameters	Load parameters	Transport software	Space requirements	Loading/unloading	Loading parameters	Dynamic parameters	Accuracy	Controller	System controller	Structure	Compatibility	Production planning and control	Relative importance	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	1	
Manufacturing System Task Requirements	1																															1
Processing	2																															2
Setup time/Part handling	3			●	●				○		●				△	○							○	●	●	○			●	△	4	3
Processing time	4			○	○	●	○	○	○		○	●	●	○	○	○													○		3	4
Tool handling	5						●	△	●					●	△	●								○	○	○		●	○		4	5
Machine utilisation	6				●	●	●	●	●			●	●	●	●	●		●		○			○	○		○		○	●	●	4	6
Number of processing	7				○	○	●	●	●			○	○	●	●	●		●		○			○	○	○	○		●	○	●	3	7
Batch size	8					○	○	○				○	○	○	○			●	○	○			○			○		○		○	4	8
Part variety	9			●	●	●	●	●	●		●	●	●	●	●	●		●	●	●			●	●	○	●		●	○	●	5	9
Machine set-up time	10			●	○	●	●	○	○		●	●	●	●	○	○													○	△	3	10
Machine reliability	11			●		●	○	●	○		●	●	●	●	●	○															5	11
Machine flexibility	12				●	●	●	●	●			●	●	●	●	●		○		○			○	△	○	○		○	●	●	4	12
Material handling	13																															13
Transfer time between machine	14																	●		●			○	○				●	●	○	4	14
Queuing time	15					○	●		○			○	○	●		○		●		●			●	●		●		△	●	●	3	15
Loading/unloading time	16								○							○				○			●	●	△	●		○	●	△	4	16
Inventory level	17					○	○		○			○	○	○		○		●		●			●	△		●		●	●	●	4	17
Material handling flexibility	18																	●	●	●	○		●	○		●		○	○	○	3	18
Material handling reliability	19																	●	○	●	△		●	●	●	●		△	●	○	3	19
Quality Functions	20																															20
Process capability	21			●		●	○	●	○		●	●	●	○	●	○												○	○		4	21
Maintenance	22							●							●						●							○			3	22
System integration	23					○	○	○	●					○	○	●		●		●			●			●		●	●	●	3	23
Absolute importance	1			198	180	303	303	295	297		198	294	294	333	299	297		336	93	282	30		294	233	115	294		281	372	297	1	
Relative importance	2			3	3	5	5	5	5		3	5	5	6	5	5		6	2	5	1		5	4	2	5		5	6	5	2	
Rank	3			2	2	4	4	4	4		2	4	4	5	4	4		5	1	4	1		4	3	1	4		4	5	4	3	
	4																														4	
Maximum total possible	5			630	630	630	630	630	630		630	630	630	630	630	630		630	630	630	630		630	630	630	630		630	630	630	5	
Column total / max total possible (630)	6			0.3	0.3	0.5	0.5	0.5	0.5		0.3	0.5	0.5	0.5	0.5	0.5		0.5	0.1	0.4	0.1		0.5	0.4	0.2	0.5		0.5	0.6	0.5	6	
#of demands addressed/max # possible (19)	7			0.3	0.4	0.6	0.7	0.6	0.7		0.3	0.6	0.6	0.7	0.7	0.7		0.6	0.2	0.6	0.2		0.7	0.6	0.4	0.7		0.8	0.8	0.7	7	
CF = 1 + (item 6 + item 7)	8	1.0		1.1	1.1	1.3	1.3	1.3	1.3		1.1	1.3	1.3	1.4	1.3	1.3		1.3	1.0	1.3	1.0		1.3	1.2	1.1	1.3		1.4	1.5	1.3	8	
Revised abs imp.	9			216	189	390	402	387	400		218	373	373	453	386	400		440	96	382	30		388	287	123	388		387	557	383	9	
Revised relative importance	10			3	3	5	5	5	5		3	5	5	6	5	5		6	1	5	1		5	4	2	5		5	7	5	10	
Revised rank	11			2	2	3	3	3	3		2	3	3	4	3	3		4	1	3	1		3	3	1	3		3	5	3	11	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29		

cfqm4 (CONSOLIDATION FACTOR)

Figure 7.12 An example of the use of consolidation factoring.

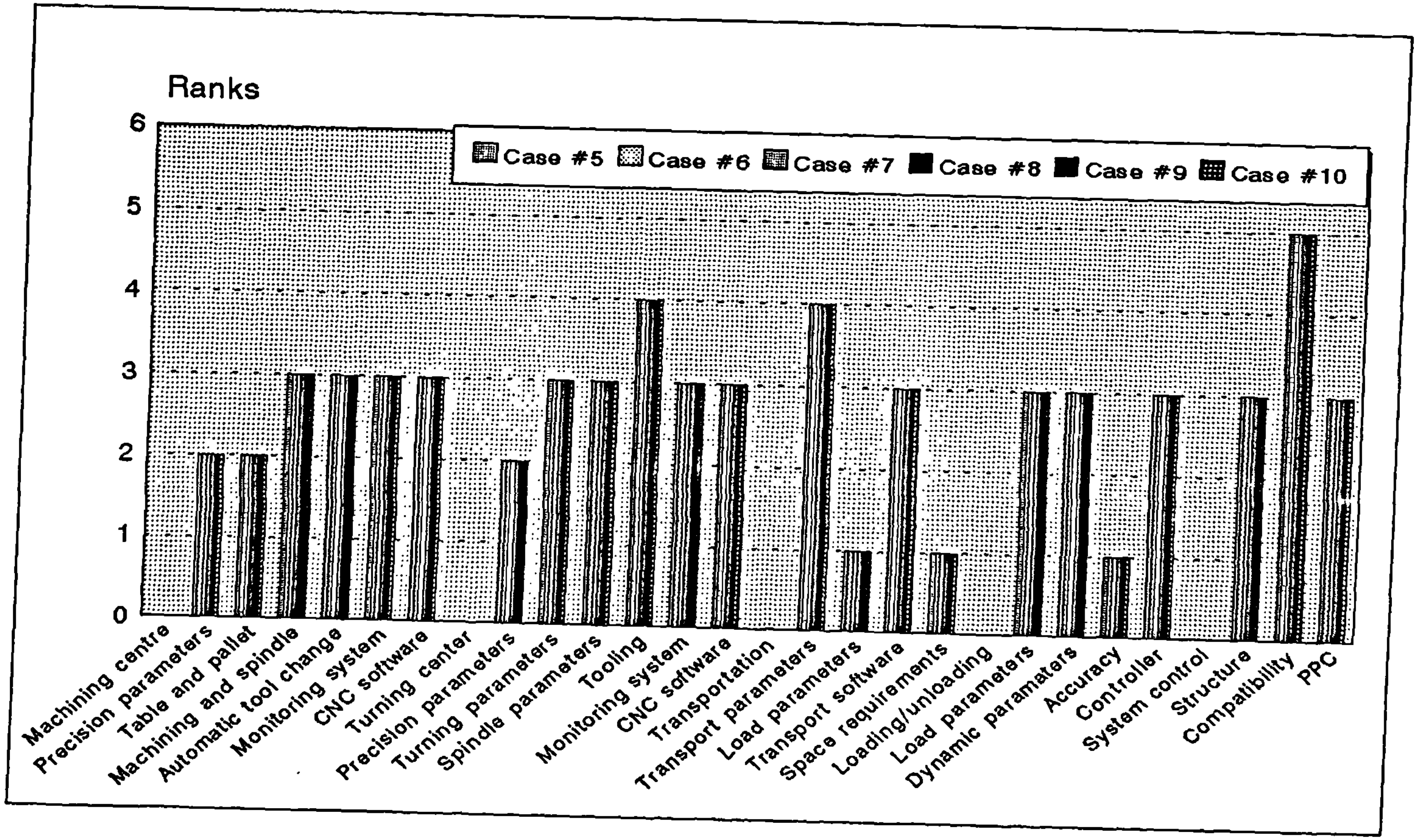


Figure 7.13 Effect of using the CF on the ranking of the parameter groups for Case #5.

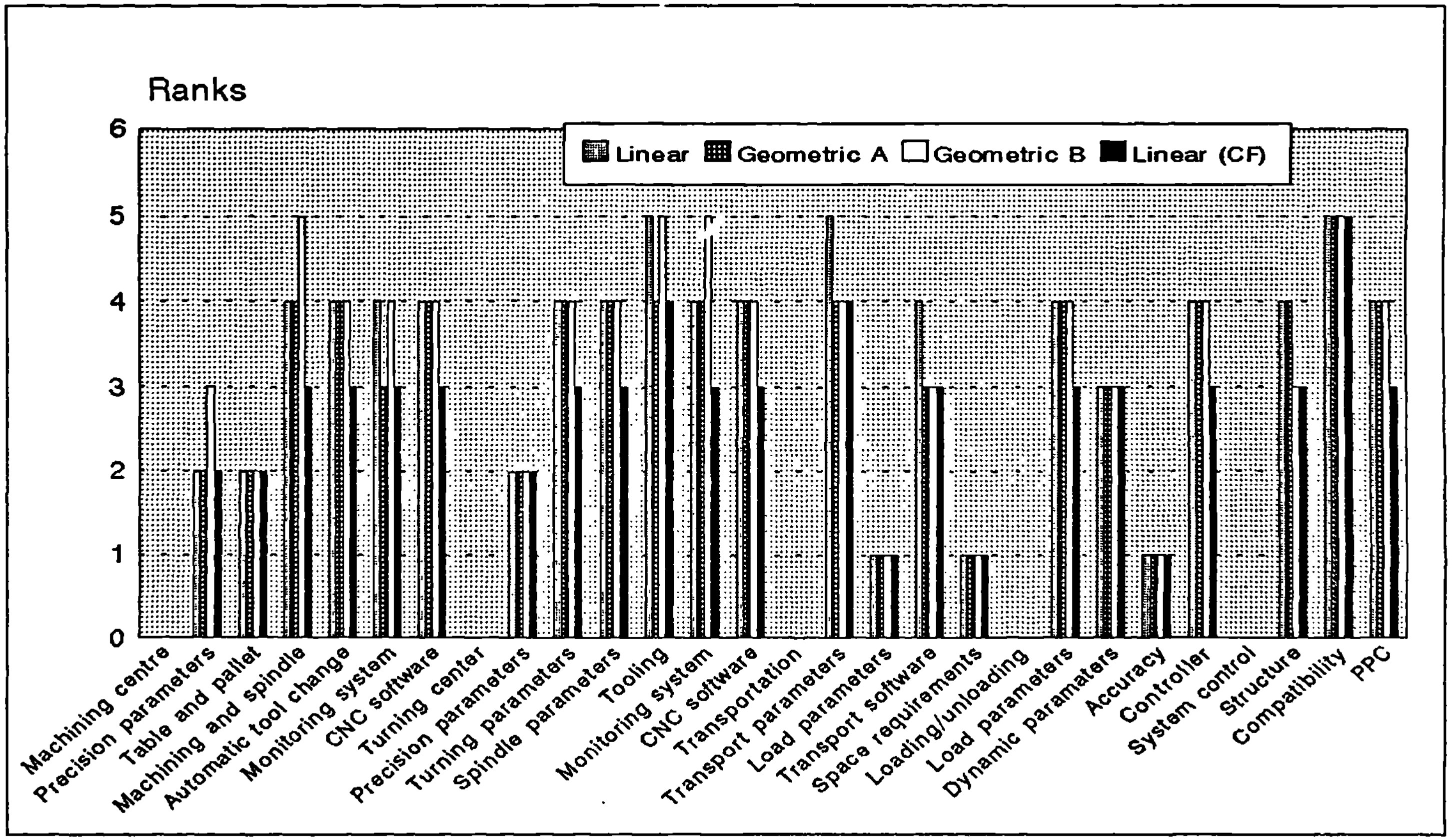


Figure 7.14 Comparison of the effect of different scales and the CF on the ranking of the parameter groups for Case #6.

7.5 Discussion

7.5.1 Evaluation of Requirements Priorities

The driving force in QFD application is that of identifying the core (or customer) requirements. Various approaches have been proposed such as the voice of customer table [175]. Once identified, there must be a rational basis for aggregating and evaluating the relative importance of the requirements. One way of getting these values is by establishing a cross-functional team and conducting the brainstorming exercise. The values of relative importance of the requirements can then be discussed and agreed upon. The advantage of this approach is that the values arrived at will represent the viewpoints of the various departments within the company and the process is technically simple. In addition the amount of resources expended would be kept to a minimum. Since decision making is through consensus, the implementation will be easier. Information, such as those from the benchmarking exercise would be useful as input. However such simplified approach lacks objectivity and does not specifically take into consideration the detail relationships that occur among the requirements. It generally depends on experience and the more influential member of the group may result in biased outcome. Hence the consistency of the judgements tend to be questionable. This means that the values of the priorities may not reflect the true company needs.

As an alternative method of assigning the relative importance the use of the Analytic Hierarchy Process (AHP) has been suggested [4, 13]. The advantage of the AHP method is its ability to handle tangible as well as non-tangible criteria, especially those in which the subjective judgements of individuals constitute an important part of the decision process. In addition, the method allows the consistency of judgements to be determined within its mechanism. This will ensure the credibility of the priority values obtained.

The values of D_i and D_j in Tables 7.2 - 7.11 had been chosen randomly, to simulate the randomness of the actual values that might be considered in practice. However this randomness posed problems with respect to obtaining priority values with a degree of consistent judgements. This is proved to be the case in Cases #1 to #4, where the values of the consistency ration (CR) are greater than 10%. This is despite the fact that the evaluation of the eigenvectors [224] yields values for the relative importance (Priority columns in Tables 7.2-7.11). This observation indicates the necessity for the decision makers to exercise care in allocating the relative importance of the strategic requirements. The practical implication of this phenomenon is that although the values obtained in the survey (Chapter 4, Section 4.3.4.2) might have provided some information into the tendency of the responding companies to allocate priorities to the elements of the manufacturing strategy, they may not reflect the true and consistent requirements of the market.

The significance of the consistency ratio (CR) is that it ensures the resulting order of priority truly represents the intensity of the decision makers' judgmental perception of the preferences of the alternative requirements, and considering the importance of the trade-offs among the choices (Chapter 2, Section 2.5.6). The notion of consistency in the present context is that, if requirement A is twice as important as B and that B is three times as important as C, then the judgement is consistent if A is taken as six times as important as C. If other value for A/C comparison is given, the judgement is said to be inconsistent. The eigenvector method permits a quantitative assessment of the consistency [224]. To facilitate obtaining consistent judgement, the format shown in Table 7.13 could be used in order to avoid ambiguity of judgements..

	Extreme	Very strong	Strong	Moderate	Equal	Moderate	Strong	Very strong	Extreme	
	9	7	5	3	1	3	5	7	9	
D1										D2
D1										D3
D1										D4
D2										D3
D2										D4
D3										D4
Dn										Dn+1

Table 7.13 Format for pairwise comparison.

For cases #5 - #10, the CRs indicated the judgements to be consistent. What is obvious from these cases is that the degree to which only one dimension is outstanding relative to the others. This is indicated by the gaps in terms of the priority values calculated, as shown in Figure 7.9. As can be observed, there is no 'ordered' manner in which the strategic requirements are arranged. As the mathematical rigour is not the emphasis, it is perceived that such outcomes are acceptable.

7.5.2 Requirements Deployment

An important factor to be considered during the deployment process is that of the relationships that exist between the WHATs and the HOWs in each of the planning matrices. Precise relationships are not the main issue in the context of the present work, as in practice they do vary from one manufacturing system to another. This is due to the different parameters influencing each relationship such as the nature of the company and products, as well as the market environment.

In the examples, the criteria used in selecting the HOWs in Planning Matrix #1 to the next phase are: (1) they are manufacturing related and manufacturing specific, i.e., the parameters are directly related and contributing to the manufacturing activities, and (2) they 'score' significant values in terms of the relative importance and hence the ranking. While criterion (2) is quite straight forward, criterion (1) needs additional judgement from decision makers as there may be cases where although the ranking is high, the HOW is not directly affecting the achievement of the WHATs, within the predefined context. As an example consider the planning matrix 1 for Case #5 (Figure 7.8a). The design and engineering cost, which has a high degree of contribution towards the low price objective (relative importance = 13%; rank = 4) was not deployed further as it was not manufacturing related and manufacturing specific, as compared to say, manufacturing lead time (relative importance = 8%; rank = 3). Similar argument is applicable for the rest of the planning matrices.

For Planning matrix #3 (manufacturing system performance deployment) additional criteria could be used in deciding which HOW is to be deployed further. Organisational difficulty in implementing the HOW could for example be included in the HOW MUCHes room, as a measure of efforts and resources that are needed by the company to implement the tasks (in the HOWs room). The resources are in terms of financial, technical and personnel. Thus when these additional criteria are considered, only those HOWs which are important and 'difficult' would be deployed. Although the correlations between the HOWs are shown (the roof of the house of quality), they were not utilised. For resource optimisation and trade-off (in which the correlations between the HOWs are used), additional data are required.

The final planning matrix relates the tasks required to be addressed by the manufacturing system, and the attributes of the manufacturing system elements (which are expressed as parameter groups). The outcome of the planning matrix in this phase is a set of rank values for the parameter groups of the system elements. These will provide supplementary qualitative criteria in the equipment selection process of the manufacturing system design. Figure 7.10d shows that for the machining centre and the turning centre, the monitoring system, the machining and spindle, automatic tool change, and the CNC software are the parameter groups which are more important than the others. For the materials handling system, the transport parameters such as speed and flexibility of movement tend to be more important than say, the load and software parameters. For the system controller, its compatibility with other elements in a manufacturing system such as the machines and materials handling systems is slightly more important than the structural issues such communication topologies, hardware and software capabilities.

The usefulness of the proposed methodology is that in the actual equipment selection process, the various system elements can be considered based on the degree of importance of their parameter groups. Thus the problem of conflict of resources can be minimised as the decision making variables will be consistent and focused and they are strategically related to the customer or market. The ranking of the parameter groups for Case #5 is shown in Table 7.14. Although these variables would have been considered in the normal selection process, what the methodology has done is not only to explicitly show the existence of the link, but also to utilise such strategic relationships in the decision making process of manufacturing system design.

System elements	Ranks	System elements	Ranks
Machining centre		**Materials handling system**	
Automatic tool change	4	Material transport	
Monitoring system	4	- transport parameters	5
Machining and spindle	4	- transport software	4
CNC software	4	- load parameters	1
Precision parameters	2		
Table and pallet parameters	2	Loading/unloading	
		- controller	4
Turning centre		- loading parameters	4
Tooling	5	- dynamic parameters	3
Turning parameters	4	- accuracy	1
Spindle parameters	4		
Monitoring system	4	**System controller**	
CNC software	4	Structure	4
		Compatibility	5

Table 7.14 Ranking of the parameter groups for Case #5 (degree of importance decreasing from 5 to 1).

Besides providing information on the significance of the various parameter groups in the fourth planning matrix, the deployment process also gives indications as to what design decisions are more important at each of the deployment stages. Based on the various strategic emphasis, the relative importance of the requirements which are shown in Figure 7.10 (a-c) are summarised in Table 7.15. The table is constructed by considering the more important (rank 4 & 5) requirements in each level of the hierarchy, and taking into account the individual case that represents the emphasis on each of the strategic objectives. The information presented in the table can be used as a guideline for manufacturing system designer when considering what aspects to concentrate upon at each level of decision making, for any give combination of strategic objectives. This could be based on the frequency of occurrence of the parameters p at the production system level, f at manufacturing system level, and t at the manufacturing system task level.

Strategic Objectives	Important requirements at each level of the hierarchy		
	Production System	*Manufacturing System Performance*	*Manufacturing System Tasks*
PRICE	p1, p2	f2, f7, f9, f10	t1, t3, t4, t6, t7, t9, t10, t11, t13, t14, t17
QUALITY	p1, p2, p3, p5	f2, f3, f7, f8, f9, f10, f11	t1, t3, t4, t6, t7, t8, t9, t10, t11, t13, t14, t17
DELIVERY RELIABILITY	p1, p3, p4, p5	f2, f3, f7, f8, f9, f10, f11	t1, t3, t4, t6, t7, t8, t9, t10, t11, t13, t14
DELIVERY SPEED	p1, p2, p3, p4, p5	f2, f7, f9, f10	t1, t3, t4, t6, t7, t8, t9, t10, t11, t13, t14
PRODUCT VARIETY	p1, p3, p4,	f2, f3, f7, f8, f9, f10, f11	t1, t3, t4, t6, t7, t8, t9, t10, t11, t13, t14, t17
VOLUME CHANGES	p3, p4, p5	f2, f3, f7, f8, f9, f10, f11	t1, t3, t4, t6, t7, t9, t10, t11, t13, t14

p1: manufacturing cost
p2: manufacturing quality
p3: production flexibility
p4: market flexibility
p5: manufacturing lead time

f1: processing cost
f2: manufacturing overheads
f3: system utilisation
f4: system throughput
f5: percentage rejects
f6: rework
f7: system reliability
f8: volume flexibility
f9: process flexibility
f10: product flexibility
f11: routing flexibility

t1: part set-up/handling
t2: processing time
t3: tool handling
t4: machine utilisation
t5: number of processing
t6: batch size
t7: part variety
t8: machine set-up
t9: machine reliability
t10: machine flexibility
t11: transfer time
t12: queuing time
t13: load/unload time
t14: inventory level
t15: material handling flexibility
t16: material handling reliability
t17: process capability
t18: maintenance
t19: system integration

Table 7.15 A summary of important requirement parameters at each level of the hierarchy.

7.5.3 Effect of Changing the Strategic Focus

Comparing the results of the final planning matrix for cases #5-10, it appears that there is no difference in the values of the final rankings for the parameter groups, as shown in Figure 7.10d. In other words, for a given parameter group, the value of the ranking is identical for all the cases. This is despite the fact that the deployments started with different values of the relative importance of the strategic objectives, as indicated by Figure 7.9. The results were quite different from what was initially expected, i.e., different strategic emphases would have resulted in different degree of relative importance (or rank) of the parameter groups. There are two possible explanations. The first is that since a linear scale had been used for the ranking of the requirements (i.e., 5-4-3-2-1), the effect of multiplying these with the values of the WHATs-HOWs relationships did not effect significant distinction in the calculated values. Or, if there were differences, they would be small, such that the values of the ranking tended to 'smooth' out in the later matrices. The second possible reason is that, since the overall performance of the manufacturing system is a result of both effective design and efficient manufacturing planning and control activities, the system design and specifications are not the absolute determinants of the success of the manufacturing system. Thus, manufacturing system design can be considered as having complimentary role in ensuring the successful operations of the manufacturing system, and in achieving the corporate objectives of the company.

7.5.4 Effect of Using Different Scales and the Consolidation Factoring on the Parameter Groups Ranking

To overcome the shortcoming mentioned in the previous section, the geometric scale and the consolidation factoring (CF) were introduced in ranking the requirements. Generally using the geometric scale seemed to affect the trends of the result on the ranking of the parameter groups only slightly as can be seen by comparing Figure 7.10d with Figures 7.11a and 7.11b. The geometric scale 'B' appears to give better distinction between the ranks of the parameter groups of the machining centre as well as the turning centre. The geometric scale 'A' however, appears to have slight impact on the parameter groups of the machining centre only. No significant effects are observed for the parameter groups of the materials handling and the system controller.

The introduction of the CF did not produce significant changes to the distribution of the parameter groups ranking, as shown in Figures 7.12 and 7.13. Comparing Figures 7.10d and 7.13, the numerical values of the ranking are actually reduced when the CF is used. This situation arises because the value of the absolute and the relative importance of the 'compatibility' group of the system controller has increased. The effect of greater revised relative importance is to reduce the ratio against which the linear scale is multiplied, thus resulting in the lower value of the ranks.

7.6 Industrial Implementation of the Methodology

In order to appreciate the issues involved in the evaluation and selection of advanced automation, it is imperative that the characteristics, benefits, and limitations of the equipment under consideration be clearly understood. The normal process of evaluation and selection of manufacturing system elements would involve operational evaluation followed by financial evaluation which involves discounted cashflow analysis. The proposed methodology, however incorporates the elements of strategic evaluation such as the market requirements dimensions and their relative importance.

The simulated examples shown in this chapter illustrate the potentials of the methodology, particularly in ensuring the consistency of the subjective judgements of the decision makers. The feasibility of successfully implementing such and integrated approach in the actual industrial setting is very much subject to organisational constraints. Although strategic consideration can contribute positively towards a more meaningful operational and financial evaluations, it may be viewed as less important in the short term by the management. Other factors that may form the organisational constraints include the lack of support and positive attitude shown by the top management, unavailability of team culture within the organisation, the absence of clear objectives for the manufacturing system planning and design team, and the lack of experience with relevant automation.

In terms of the technicality of implementing the methodology, the design team should carefully consider all the technical or manufacturing parameters at one level of the requirement hierarchy that fulfil the need of the requirement at the next higher level. This step is necessary to ensure that the strategic requirements are truly and accurately addressed. Successful implementation is also dependent upon the measures of the requirements (the HOW MUCHes), especially in defining manufacturing system performance requirements and manufacturing system task requirements. The numerical values may not be precise, but realistic values of these requirements will narrow down the options for the parameter groups of the manufacturing equipment.

7.7 Summary

The chapter has described the initial attempts to verify the proposed manufacturing system design methodology. The pairwise comparison of the strategic requirements indicated the significance of the consistency of judgements in allocating priority to their relative importance. The priority values for price, quality, delivery reliability, delivery speed, product variety and volume changes were arrived at using the Analytic Hierarchy Process (AHP). Based on the different combinations of the priorities obtained, the requirements were deployed using four planning matrices which had been previously defined. The deployment process was accomplished using the QFD/CAPTURE package. The final matrix provided information in the form of rank values for the various parameter groups of the system elements which are useful during the equipment selection phase of manufacturing system design. The values of the parameter groups ranking were not significantly affected by the type of scales used and the introduction of the consolidation factoring. The ranking of the intermediate variables in the earlier planning matrices can be used as guidelines for focusing the decision making process and the optimisation of resources during manufacturing system design.

CHAPTER 8

CONCLUSIONS

This chapter concludes the research work reported in this thesis. The main themes which have been explored in the thesis are the major elements that constitute manufacturing system design, the growing importance of the relationship between manufacturing strategy and manufacturing system design, and the prevalent methodologies and approaches for manufacturing system design both in terms of the theoretical development as well as that of the industrial practices. Lastly the applicability of the principles of Quality Function Deployment in a methodology for manufacturing system design was explored with respect to the development of the theoretical framework as well as the initial verification.

8.1 Overview of the Research Findings

The primary functions of manufacturing system design are categorised as part (selection and description, machine and equipment selection, and determination of the optimal configuration) Within each function there are other design decisions that need to be undertaken. Manufacturing system design is a complex process when viewed from both the internal, as well as the external perspectives. Internally the design process is involved with the dynamic multi-criteria and multi-objectives tasks which require trade-offs and resource optimisation. The application of computers and communications technology to all aspects of manufacturing is changing the fundamental nature of the factory. Externally, manufacturing organisations are faced with ever increasing competition and the volatility of market demands. Cost and quality are not the only determinants of success, as the customer is demanding a wider range of products at the higher degree of volume fluctuations. In addition there is increasing requirements for the delivery to be reliable and faster.

The design decisions in manufacturing system design problems range from the strategic level to the tactical and operational levels. At each level the major task of design is to achieve design objectives by mapping the appropriate decision variables onto specific performance requirements. Although the relationships can easily be expressed analytically at the operational and tactical levels, it is much more difficult at the strategic level due to the fuzziness of the relationships.

A comprehensive but concise literature survey is reported in Chapter 2 on subjects related to the conceptual understanding and the design and development of advanced manufacturing systems. It summarises and updates the previous research efforts on the development of methodologies and tools for manufacturing system design. These include the phased approach to design and implementation, the manufacturing systems engineering analysis, the axiomatic approach, the structured methodologies, the use of modelling and simulation, the applications of operational research techniques and the use of artificial intelligence. The manufacturing system design solutions using most of these approaches are local optimisation in nature, which normally involve decomposing the design problems into sub-problems which are then treated separately. Optimal solutions to the simplified problems are found based on certain assumptions. No single design tools can be used for solving all aspects of system design problems. Instead, the use of different design tools at different stages of advanced manufacturing system design must be incorporated.

Although the solution techniques are widely publicised in the academic literature, they are not extensively applied in industrial practice as indicated by the empirical study of the survey findings. Among the reasons cited for such minimum level of application are vague objectives and poor requirements specifications and unavailability of personnel with sufficient skills. Nevertheless, the majority of the respondents who use one or more of the techniques and tools have reported improvements in their design efforts. In general a higher percentage of the tools used are in the analysis stage of the design process.

The importance of manufacturing companies having a clear manufacturing strategy which is covered in the literature review is further emphasised by the survey results. The performance of companies with manufacturing strategy seem to be much better than those without. Despite the prominence being given to flexibility as a strategic weapon to succeed in the competitive market, the survey indicates that the sample of the UK manufacturing companies do not regard it as such. In fact, the 'order' of relative importance of the competitive advantages appears to be quality, delivery, cost and flexibility. The order suggests that there is a changing trend in addressing these competitive advantages, particularly that of cost. In terms of flexibility, greater emphasis is being placed on system and expansion flexibilities. There is also a marked decrease in terms of product flexibility when compared to the previous studies.

The research has also shown the growing interest in addressing the relationship between manufacturing strategy and manufacturing system design decisions. Although a number of models have been proposed, there is still apparent ambiguity within the manufacturing industry as to how this relationship is to be operationalised. Hence a need has been identified to develop a methodology to address this issue.

Quality Function Deployment (QFD) as a system for designing a product or service based on customer demands is increasingly being used by the manufacturing industry. The conceptual framework of the approach is built around the core items of moving the quality issues upstream, customer satisfaction mindset, people and teamwork, and connectedness. Besides product design, the principles of QFD have also been applied in numerous other applications which range from the construction industry to the academia. The last part of this thesis concerns the development of a manufacturing system design methodology based on the principles of QFD. Initial verification tests indicate the suitability of such application.

8.2 Contributions of the Thesis

The following contributions are made to the knowledge of advanced manufacturing system design. The initial studies indicate the gap that still exists between academic perspective of the manufacturing system design and development methodologies and the industrial applications. Despite the existence of models that relate manufacturing strategy and manufacturing system design decisions, little research has been done toward a generic guideline or procedure for implementation. In general, the second part of the research has developed a procedure which combines the principles of Quality Function Deployment with the technique of Analytic Hierarchy Process for application in the design of manufacturing system. This has been achieved through the following stages:

- Theoretical framework and justifications have been put forward regarding the suitability of the principles of quality function deployment to be applied in the design of manufacturing systems. A positive correlation was observed between the QFD concepts and the set of criteria for manufacturing system design.

- Development of a framework for the deployment of the strategic requirements of price, quality, delivery and flexibility into manufacturing system design variables. The framework is based on the top-down decomposition of the strategic requirements into their constituent elements. These elements are then arranged into a hierarchy of requirements in a manufacturing organisation. The levels in the hierarchy are: production system requirements, manufacturing systems performance requirements, manufacturing system tasks requirements and manufacturing systems elements requirements. The assumption at this stage is that the elements within each level of the hierarchy influence the group of elements in the hierarchy above it. The elements in each group being independent of each other.

- The deployment of the requirements is achieved through the use of planning matrices which related one level of requirements in the hierarchy to another. The selection of the HOWs (the parameters to meet the requirements) for further translation involves consideration of the relative importance of the requirements (the WHATs) and the strength of the relationship between the WHATs and the HOWs. The initial priority values of the strategic requirements are evaluated using pairwise comparison of the Analytic Hierarchy Process.

- In the final planning matrix a set of parameter groups of the system elements which are ranked according to their relative importance is obtained. It is used as a complimentary criteria for system elements selection.

- The use of the methodology is illustrated by the equipment selection problem. The examples have identified the limitations and some potential improvements to the methodology.

The methodology has a number of advantages over other methods. Fundamentally, the methodology has managed to integrate manufacturing strategy and manufacturing system design decisions. This integration has been fully utilised in developing the framework. Through the evaluation of the relative importance of the strategic requirements and their subsequent derivations the methodology has attempted to include quantitative features into the typically qualitative decision making process. The deployment process itself results in the decisions made to be more focused and highly tractable. This is because the decision to deploy further any of the parameters that fulfil the requirements (HOWs) is subject to the parameters being related and specific to the problem area being addressed. The decomposition of the requirements at each level of the hierarchy ensures that only the most important parameters are considered. The focusing of design variables increases the optimum utilisation of organisational resources. Because the use of planning matrices has been made of, there is a degree of transparency to the decision making process. Hence communication among the designers will be improved.

By considering the more important requirements at the production system, manufacturing system performance and manufacturing system task within the hierarchy, the methodology provides a useful guideline to systems designer on design aspects that need to be focused for a given combination of strategic requirements.

The methodology presented can also be further developed as a device to train the shopfloor workers on quality improvements. The relationships that are shown in the planning matrices will allow personnel in each level of the hierarchy to recognise and identify the significance of his/her contributions to the overall corporate objectives.

8.3 Limitations and Suggestions for Further Work

It is evident that a systematic approach is needed to design and develop manufacturing systems efficiently, instead of ad-hoc procedure for developing designs. The literature review indicates that no single design methodology or tool can be used for solving all aspects of systems design problems. Instead, the use of different design tools at different stages of advanced manufacturing system design must be considered. A methodology incorporating the QFD principles and the AHP technique is proposed in this thesis which addresses the relationship between manufacturing strategy and certain aspects of manufacturing system design decisions. Based on the methodology development and examples, a list of further research topic emerges:

- Although it is sufficient to illustrate the principles behind the proposed methodology, the data for the case examples may not be representative of an industrial situation. Hence, further studies could be conducted to examine the appropriateness of the tools used for different environments.

- The degree of distinction or contrast between the different HOWs, particularly in the last planning matrix has been a problem in the examples. Although different scales have been used and the consolidation factoring has been tried, it appears that there is not much difference in the trends of the ranking values of the parameter groups. This situation may not be too encouraging for the decision makers. Hence, further investigations on suitable scaling factors will be useful to address this limitation.

- As elaborated in the thesis, the numerical criteria for deployment purposes are based on the strength of the WHATs-HOWs relationship. It would be useful to test the effects of other parameters such as organisational difficulties as additional criteria or guidelines for selecting and deploying the HOWs.

- Following the previous suggestion, the possibility of employing an expert system to handle the massive information and the complex relationships could be investigated.

- The methodology has been developed based on the structural issues of manufacturing system design. However, decisions related to structure and operations of the system cannot be evaluated independently during the system design process. Hence the methodology can be extended to address operational decisions such as the maintenance policies, inspection policies, as well as those related to production planning, scheduling and control.

The systematic procedure for the proposed methodology described in this thesis is in embryonic stage. The philosophies and approaches require further testing and validation, in order to draw a comprehensive conclusion regarding the success and limitations for industrial applications.

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APPENDICES

Appendix A

Range of Advanced Manufacturing System Configurations

Processing system strategy	Material handling system strategy	Tool handling system strategy	Quality assurance strategy	System integration strategy	System configuration type
Transfer line	Operator-assisted MHS	Manual tool changeover	Manual offline inspection	—	Transfer line (automated)
Operator-assisted NC machine	Operator-assisted MHS	Manual tool changeover	Manual offline inspection	—	Operator controlled NC machine cell
Multi-machine FMS	Computer-controlled MHS	Manual tool changeover	Automatic online inspection	—	Traditional FMS with multiple machines
Multi-machine FMS	Computer-controlled MHS	Automated tool delivery	Automatic online inspection	Integration with CAD/CAM	Traditional FMS with CAD/CAM
Integrated CNC machine	Computer-controlled MHS	Automated tool delivery	Automatic online inspection	—	Flexible Manufacturing cell (FMC)
Integrated CNC machine	Computer-controlled MHS	Automated tool delivery	Automatic online inspection	Integration of multiple FMC	FMS with multiple FMC
Integrated CNC machine	Computer-controlled MHS	Automated tool delivery	Automatic online inspection	Multiple FMC with CAD/CAM integration	FMS with multiple FMC and CAD/CAM
Integrated CNC machine	Computer-controlled MHS	Computer-controlled tool migration	Feedback for automatic process control	Multiple FMC with CAD/CAM integration	FMS with CAD/CAM and automatic process control
Integrated CNC machine	Integrated MHS with AS/RS	Computer-controlled tool migration	Feedback for automatic process control	Integration with CAD/CAM and MRP II	Fully integrated FMS with CAD/CAM, AS/RS and MRP II

Appendix B

WITNESS Simulation Case Study

1. Introduction

This case study illustrates the application of WITNESS discrete system simulation in the redesign of a manufacturing system. The author was involved in the first six months of the project (July-December 1994) when it was initiated.

The company involved is BICC Cables Ltd. in Wrexham. The plant in Wrexham manufactures cables for power transmission. The cables are made up of appropriate number of wires applied (stranded) in layers, each layer being shaped and compacted to form the required size and shape.

The system under investigation is the wire drawer and strander section. The system consists of six wire drawers, six stranders and one wiring station. These machines are connected via a network of conveyors. The wire drawers produce bobbins which are delivered and mounted on the stranders via shuttle conveyors and loaders. Each of the stranders can accept a number of bobbins depending on the size and type of power cable produced. Each of the stranders contains a number of carriages and spindles in each. Each set of spindles holds 3 bobbins. Empty or close to empty bobbins are unloaded from the stranders and fed to the wiring station where any remaining wire lengths are welded together to make up a full bobbin.

2. Project Objective

- Development of a simulation model to represent the strander operations currently running at BICC Wrexham Plant. The model will be developed in Witness for Windows version 5.0.

- To use the model to test and evaluate the various scenarios/rules with the aim of improving the performance of the system.

3. Current Operating Conditions

a) Manning:

- Each of the wire drawers are manned by a single operator.
- Each of the stranders is manned by a single operator who is responsible for loading and unloading bobbins and attending to machine breakdown.
- The wiring station is manned by a single operator for welding and recycling cables from spent bobbins.

b) Bobbins:

- For each job (i.e. finished strand cable) bobbins are usually the same length (from 5 to 10 Km).

c) Wire drawers

- The wire drawers operate at speeds of approximately 20 m/sec.
- Wire lengths in bobbins are currently not accurately controlled which results in bobbins varying in length by approximately ±10%. However, this will be rectified with the proposed overhaul.

d) Stranders

- There are four main configuration of stranders. The stranders can consist of two, three, four or five carriages. There are six stranders in total, three stranders with three carriages each and one strander from each of the other types.
- Wire is pulled from the bobbins at speed of approximately 60 m/min. This rate varies depending on the position of the bobbin in the machines. The further the carriage is from the finished cable the lower the rate of wire extraction.
- A single bobbin is used at the back of the strander to feed a core wire.
- It takes an operator approximately 2 to 3 minutes to unload an empty bobbin, load a new bobbin and join by welding the ends of the wire.
- Strander breakdown usually occupies up to 15% of operation time.
- At the moment it is not possible to load more than one bobbin at a time on each carriage. This might change in the future.

e) Conveyors

- Each strander is fed bobbins using a single dedicated conveyor which runs parallel to the strander axis. Each carriage on the strander is served by a shuttle conveyor which moves closer to the carriage for loading and unloading of bobbins.
- Conveyors are of the queue type and operate at a fixed speed. For the purpose of modelling the bobbins speed will be approximately one bobbin width every 5-10 seconds.
- Each strander conveyor has a buffer of 3 bobbins.

4. Project Details

As described in BICC document, the project will be carried out in three phases. The first phase will concentrate on modelling one of the three carriage stranders with various rules for manning and delivery of bobbins. The rules are listed in the BICC document. The second phase will involve modelling the operations from one wire drawer to the strander for one size of strand. The third phase will involve modelling the entire system including the material handling equipment. The measure of performance will be the strander and operator utilisation.

Phase I: Modelling strander A01

This A01 strander consists of three carriages with two, five and seven spindles respectively. Each spindle carries three bobbins which results is a total number of bobbins of 43 (this number includes the bobbin which feeds the core wire). This strander is currently manned by one operator. The initial part of phase I is to model the system as it exists at the moment. This initial model will be validated by comparing the results with monthly data provided by BICC.

5. Modelling the System

Initial Model Assumptions

1) As the process in this system is a mixture of continuous and discrete operations an approximate approach is necessary to convert the continuous operations (i.e. extracting wire from the bobbins) to discrete ones. The approximation involves assuming that at the stage of loading a bobbin on the strander the wire carried by that bobbin is split into discrete fixed lengths of wire. For example, a 5000m bobbin could be represented by 500 ten metre discrete wires which are pulled by the strander one at a time. This means that the loading equipment will be represented by a production machine where the input part is one full bobbin and the output parts are 'n' lengths of wire and an empty bobbin. The wire parts are pushed to a buffer for use by the strander and the empty bobbin is stored in a temporary buffer.

2) The unloading process is carried out by a single machine which pulls an empty bobbin from the buffer and places it on the conveyor. Since in the real system the loading and unloading machines are the same, the model will have to make sure that only one machine can operate at any one time.

3) Each position on each spindle (i.e. where a full bobbin is placed) is represented by a buffer. These buffers hold the discrete lengths of cable and are pulled from by the strander to make up the finished strand.

4) The strander will be represented by an assembly machine which pulls from the individual buffers that represent full bobbins using a fixed sequence and produces discrete lengths of finished strands.

5) In the actual strander, wire is pulled from bobbins at different rates depending on which carriage they are placed on. There are two ways of representing this in the model. The first is to set the input rules for the strander so that it pulls parts from the buffers in preset proportions representing the varying rates. The second is to vary the length of

the discrete wires stored in each buffers and therefore buffers will have different number of discrete wire parts. Information on the various rates of pull will be provided by BICC.

6) Each of the loading, unloading and breakdown operations requires an operator.

5.1 Data Collection and Verification

During the course of model construction, relevant data and information were obtained from engineers on site. This regular consultation with the systems experts is necessary to verify that the model is an accurate representation of the system.

5.2 Initial Model Entities

There are two kinds of modelling elements in WITNESS, the *physical elements* which represent tangible components of the real-life situation under study, and *logical elements*, which represent the conceptual aspects of the model.

The physical elements (or entities) used to describe the initial model are:

i) Parts

- F: A full bobbin.
- E: An empty bobbin.
- C: Discrete lengths of cable.
- S: Finished strand.

ii) Machines

L0: Loader for the core bobbin. A production machine which accepts F as input and produces E and n*C as out put. Where `n' to be set at run time.

U0: Unloading machine for the core bobbin. Moves empty bobbins E to conveyors.

L1, L2, L3, L4: Loaders for carriages 1, 2, and 3.

U1, U2, U3, U4: Unloaders for carriages 1, 2, and 3.

STRANDER: An assembly machine which selects and assembles discrete C parts into a finished product, S.

iii) Conveyors

C1, C2,C3, C4: Conveyors for moving parts from buffers to shuttle conveyors.

SC1, SC2, SC3, SC4: Shuttle conveyors for carriages 1, 2, 3.

iv) Labour

Bob: Operator required for loading, unloading of the L's and the U's, and for repair breakdown of strander.

v) Buffers

- BF_IN: Input buffer to receive full bobbins F.
- BE_OUT: Output buffer to receive empty bobbins E.
- BS_OUT: Output buffer for finished strand S.
- BO: Buffer to hold discrete cable parts C for the core bobbin.

- Bxyz: Buffers to hold discrete cable parts C where 'x' represents carriages 1,2, or 3, y' represents the spindle position in each carriage (2, 5 and 7) and 'z' the spindle leg in each spindle (1,2 or 3).
- BUFExyz: Temporary buffer to hold empty bobbins `E' for each spindle.

The logical elements of the model are used to qualify the operation of the model. Variables and shift patterns are the two logical elements mostly used in the strander model. The following are the variables:

- EBxy: Tells the unloader where the empty bobbin come from. (Always set to 0).
- BExyz: Tells the loader which buffer (spindle leg) for C is empty.
- STAGE0: States whether or not the core wire spindle is empty.
- STAGE1: States whether or not any spindle in carriage 1 is empty.
- STAGE2a,b: States whether or not any spindle in carriage 2 is empty.
- STAGE3a,b: States whether or not any spindle in carriage 3 is empty.
- LUDO0,1,2,3,4 (Loader Unloader Do Once): Ensures unloader operates once before the loader can operate. Then unloader must work again.

5.3 Initial Model Rules

The rules such wait, push and pull, sequence etc., describe how the entities interact to simulate the operations of the system.

Once physically modelled, the system was operated under initial push /pull and wait rules. This allowed parts transfer problem to be discovered. The second stage introduced line control analogous to that in the plant into the low level model. The single push/pull rules were altered into more complicated IF rule. The situation where a machine is prevented from operating if the upstream conveyor is nearly empty, or the downstream conveyor is nearly full was modelled. Finally the effects of breakdowns were investigated.
Due to space limitation, only representative rules are listed in this Appendix as shown in Figure B.

6. Results and Discussions

6.1 Modified Assumptions

During model development, changes need to be made to the initial assumptions, as further information and details of the line were obtained and system restriction came into being. The process requires the conversion of the continuous wire into discrete lengths, these lengths are now 15m instead of 10m (system restrictions on the number of part C); also 33 of these 15m lengths when stranded (part S) are combined to produce a 495m cable (part CABLE).

Each of the loading, unloading and breakdown operations require an operator (BOB). Loading time: 3.5 minutes; Unloading time: 2.0 minutes; Strander breakdown: 3.0 minutes (20 minutes accumulated run time for time-to-failure). The loading and unloading times for various machines do not take into account of their relative position to the labour (BOB is usually at the strander end) i.e., BOB's walking time is not considered. Model assumes if BOB is available then he is able to start work immediately which may not be the case.

The cycle time for the conveyors (time for bobbin to move one bobbin length) has been taken as 5 seconds. The bobbin is prevented from moving onto the shuttle conveyor until there are no parts on the shuttle conveyor or the next fixed conveyor.
The breakdown figure of 15% was initially used on a Busy Time basis, where the strander accumulated run-time up to the stated time of 20 minutes at which point it then broke down for 3 minutes.

The shifts were given an arbitrary delay of 15 minutes at the start and end of each shift (to model the delay at the start and end of each shift due to washing hands, etc.). Also the break times have been modelled to exactly 30 minutes, which occur three time in a shift.

6.2 Improved Strander and Labour Utilisation

There were two main changes to be tested, firstly feeding more than one bobbin at a time (two , three). secondly testing the effects of more than one labour (two or three men). The measure of the system performance would be the percentage of labour and strander utilisation.

It was nor possible for the system to continue operating when fed with two/three bobbins at a time because a spare full bobbin would not be used and would eventually reside on the fixed conveyor before the stage three shuttle conveyors, and eventually this would jam the conveyor as empty bobbins from stage two came down the conveyor. However, a combination of the three rules was found to work.

This combination used the following technique: three bobbins are held on the first conveyor (just before the feed point for the central wire), and one is held on the fixed conveyor before stage two only being allowed to progress onto stage three when stage three has an empty spindle.
When stage one has an empty spindle the bobbins are pushed straight onto the shuttle conveyor, when stage two has an empty spindle an extra bobbin is allowed into the system resulting on two bobbins residing on the fixed conveyor before stage two, otherwise only one spare bobbin is kept on the fixed conveyor before stage two and another bobbin is only allowed into the system when the one on the fixed conveyor has moved onto stage three (reduces the transfer time of the bobbin to stage three).

The use of two/three men was a lot simpler to model and the effect of extra labour was tested on the model with the new loading sequence. However, there was no increase in utilisation with the use of three men.

6.3 Results for the Analysis of the Initial Model

The following table shows the results obtained from the initial model developed. The standard model refers to the cycle time of 5 seconds for the conveyors (time for bobbin to travel one bobbin length).

Scenario	Strander utilisation, %	Labour utilisation, %	Cable production, m per week
Standard model	31.26	25.60	94515
Standard model (10s)	28.12	23.15	85035
Standard model (10s + available time)	25.78	26.34	77995
New loading sequence	33.06	27.83	99960
NLS + 2 men	35.17	14.07	106350

6.4 Discussions

The validation process proved difficult due to the fact that there are only single specific days when the relevant cable size (36 bobbins, 1.83mm wire diameter) was produced for the production information provided for January 1994. The relevant ones are Day 3, Day 4, Day 7, and Day 21. These days give an average daily production figure of 13697m of cable (68486m per week, five days).

The model gives a production figure of 18903m per day which is 94515m per week. The error between these two figure (model/plant) is 38.00% greater for the model. This error could be due to either incorrect model assumptions or faults in the method used to compare the factory data. Another source of error could also be the lack of information on breakdowns. The arbitrary figure of 15% breakdown for strander operation time may be different from the actual value (or not of the same fixed distribution).

The cycle time for the conveyors (time for bobbin to move one bobbin length) has been taken as 5 seconds. As shown in the table, a cycle time of 10 seconds reduces the model production to 85035m, i.e., reducing the model/plant error to 24.16%. However this will marginally reduces the strander and labour utilisation.

When the breakdown figure of 15% is considered for the Available Time then the strander breaks down every 20 minutes for 3 minutes. This reduces the model's production further to 77955, as well as the model/plant error to only 13.83%. This error is equivalent to a value of 1893m of cable per day extra production by the model (one hour's extra run time for the strander). As expected the strander utilisation drops further, while the labour utilisation increases to attend to the breakdowns.

The results show that implementation of the new loading sequence has positive effects on the strander and labour utilisation, as well as the weekly production. The increase of 5.78% (5445m per week) can be attributed solely to the saving made in bobbin transfer time.

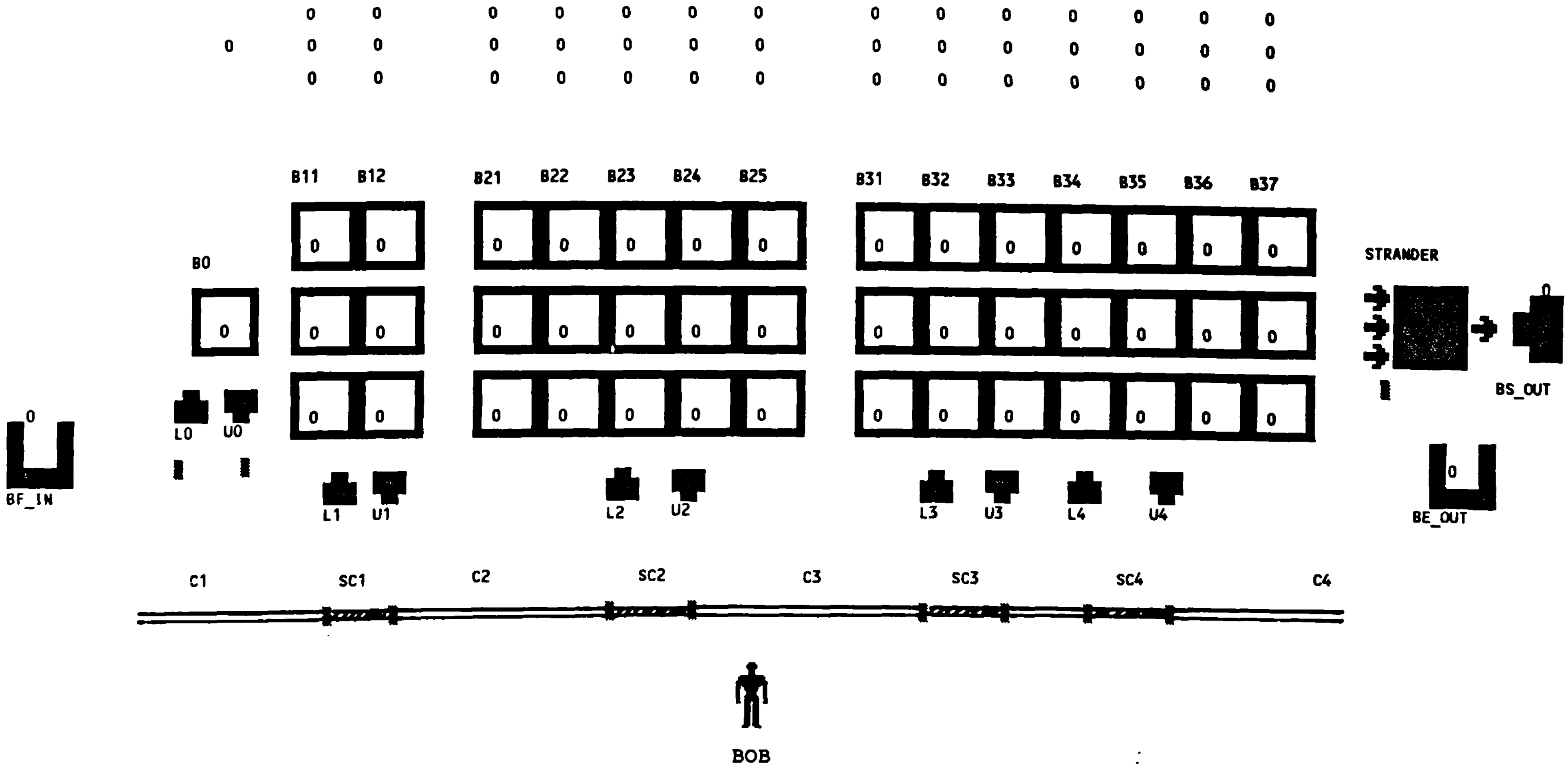
The strander utilisation can also be increased by using two men. This is due to the reduction in delay to operate the load/unload, consequently reducing the time required to refill the stages and subsequent strander idle time. The price for this benefit is that the labour is idle for even more of the time. However if there are other machines within the area that are also the responsibility of the labour then the idle time will be reduced. It is found that there was no increase in utilisation with the use of three men.

7. Conclusions

At this stage the model is yet to be completely validated by determining if the information and assumptions made so far have been correct. In addition more detailed data on breakdowns within the system is required.

Despite being at its initial stage, the project has shown the merits of using computer simulation in the design (redesign) of manufacturing systems. All the possible scenarios can be tested and compared to one another. The results of such tests can become good basis for decision making on capital investment or worker recruitment. They can also supplement the outcome of cost analysis. Other benefits include reduced risk and greater understanding of the process.

Simulation is more an exercise in analysis of the system (plant) elements than programming on computer. The primary requirement is to obtain all the information on the elements, how they work, all control logic, and any unusual operations/alterations performed by the operator. All this information can then be used to design a model to the analyst preference. If this model with all the assumptions is then presented to the system experts, any shortcomings can be detected and overcome. A model developed in this way has more chance of being an accurate model of the system than one developed in isolation.



BICC WREXHAM PLANT, LINE A03

Representative Rules

F

NAME OF PART: F;
TYPE: Variable attributes;
GROUP NUMBER: 1;
MAXIMUM ARRIVALS: 0;
OUTPUT RULE: Wait;
PART ROUTE: None
REPORTING: Yes;
CONTAINS FLUIDS: No;
SHIFT: Undefined;

END F

E

NAME OF PART: E;
TYPE: Variable attributes;
GROUP NUMBER: 1;
MAXIMUM ARRIVALS: 0;
OUTPUT RULE: Wait;
PART ROUTE: None
REPORTING: Yes;
CONTAINS FLUIDS: No;
SHIFT: Undefined;

END E

C

NAME OF PART: C;
TYPE: Variable attributes;
GROUP NUMBER: 1;
MAXIMUM ARRIVALS: 0;
OUTPUT RULE: Wait;
PART ROUTE: None
REPORTING: Yes;
CONTAINS FLUIDS: No;
SHIFT: Undefined;

END C

CABLE

NAME OF PART: CABLE;
TYPE: Variable attributes;
GROUP NUMBER: 1;
MAXIMUM ARRIVALS: 0;
OUTPUT RULE: Wait;
PART ROUTE: None
REPORTING: Yes;
CONTAINS FLUIDS: No;
SHIFT: Undefined;

END CABLE

Rules for parts.

```
B11

NAME OF BUFFER: B11;
QUANTITY: 1;
CAPACITY: 1000;
DELAY TIME : Undefined;
INPUT POSITION: Rear;
OUTPUT SCAN FROM: Front;
* Select: First;
ACTIONS, Out
Add
  BE111 = 0
End Actions
REPORTING: Individual;
SHIFT: Undefined,0;

END B11

B12

NAME OF BUFFER: B12;
QUANTITY: 1;
CAPACITY: 1000;
DELAY TIME : Undefined;
INPUT POSITION: Rear;
OUTPUT SCAN FROM: Front;
* Select: First;
ACTIONS, Out
Add
  BE121 = 0
End Actions
REPORTING: Individual;
SHIFT: Undefined,0;

END B12

B22

NAME OF BUFFER: B22;
QUANTITY: 1;
CAPACITY: 1000;
DELAY TIME : Undefined;
INPUT POSITION: Rear;
OUTPUT SCAN FROM: Front;
* Select: First;
ACTIONS, Out
Add
  be221 = 0
End Actions
REPORTING: Individual;
SHIFT: Undefined,0;

END B22
```

Rules for Buffers.

```
STRANDER

NAME OF MACHINE: STRANDER;
QUANTITY: 1;
TYPE: Assembly;
* Assembly quantity: 36;
PRIORITY: Undefined;
LABOR:
  Repair: BOB;
  Pre-empt level: None;
END
LABOR:
  Cycle: BOB;
  Pre-empt level: None;
END
DISCRETE LINKS :
       Fill: None
END
DISCRETE LINKS :
       Empty: None
END
CYCLE TIME: 0.5;
BREAKDOWNS: Busy time;
* Down interval: 20.0;
* Repair time: 3.0;
* Scrap part: No;
* Setup on repair: No;
ACTIONS, Finish
Add
  CHANGE C to S
End Actions
INPUT RULE: SEQUENCE /Wait B0(1)#(1),
            B11#(1),
            B112#(1),
            B113#(1),
            B12#(1),
            B122#(1),
            B123#(1),
            B21#(1),
            b212#(1),
            b213#(1),
            B22#(1),
            b222#(1),
            b223#(1),
            B23#(1),
            b232#(1),
            b233#(1),
            B24#(1),
            b242#(1),
            b243#(1),
            B31#(1),
            b312#(1),
            b313#(1),
            B32#(1),
            b322#(1),
            b323#(1),
            B33#(1),
            b332#(1),
            b333#(1),
            B34#(1),
            b342#(1),
            b343#(1),
            B35#(1),
            b352#(1),
            b353#(1),
            B36#(1),
            b362#(1);
OUTPUT RULE: PUSH to TRANSFER;
REPORTING: Individual;
SHIFT: Undefined,0,0;

END STRANDER
```

Rules for Strander.

L1

```
NAME OF MACHINE: L1;
QUANTITY: 1;
TYPE: Production;
* Part type: C;
* Production qty: IUNIFORM (585,611,2);
PRIORITY: Undefined;
LABOR:
  Repair: None;
END
LABOR:
  Cycle: BOB;
  Pre-empt level: None;
END
DISCRETE LINKS :
       Fill: None
END
DISCRETE LINKS :
       Empty: None
END
CYCLE TIME: 3.5;
BREAKDOWNS: No;
ACTIONS, Start
Add
  ludo1 = 1
  IF NPARTS (B11) = 0 AND NPARTS (B112) >= 0 AND NPARTS (B113) >= 0 AND NPARTS (BUFE11) = 0
   BE111 = 1
  ELSE
   BE111 = 0
  ENDIF
  IF NPARTS (B11) >= 0 AND NPARTS (B112) = 0 AND NPARTS (B113) >= 0 AND NPARTS (BUFE112) = 0

  BE112 = 1
 ELSE
  BE112 = 0
 ENDIF
 IF NPARTS (B11) >= 0 AND NPARTS (B112) >= 0 AND NPARTS (B113) = 0 AND NPARTS (BUFE113) = 0
  BE113 = 1
 ELSE
  BE113 = 0
 ENDIF
 IF NPARTS (B12) = 0 AND NPARTS (B122) >= 0 AND NPARTS (B123) >= 0 AND NPARTS (BUFE12) = 0
  BE121 = 1
 ELSE
  BE121 = 0
 ENDIF
 IF NPARTS (B12) >= 0 AND NPARTS (B122) = 0 AND NPARTS (B123) >= 0 AND NPARTS (BUFE122) = 0
  BE122 = 1
 ELSE
  BE122 = 0
 ENDIF
 IF NPARTS (B12) >= 0 AND NPARTS (B122) >= 0 AND NPARTS (B123) = 0 AND NPARTS (BUFE123) = 0
  BE123 = 1
 ELSE
  BE123 = 0
 ENDIF
```

Rules for Loading.

```
End Actions
ACTIONS, Finish
Add
  CHANGE F to E
  DESC = E
End Actions
INPUT RULE: !TO ONLY OPERATE IF THE UNLOADER IS NOT BUSY, AND SPINDLE EMPTY
            IF ISTATE (U1) = 2
             Wait
            ELSEIF NPARTS (B11) = 0
             PULL from F out of SC1 at (1)
            ELSEIF NPARTS (B112) = 0
             PULL from F out of SC1(1) at (1)
            ELSEIF NPARTS (B113) = 0
             PULL from F out of SC1(1) at (1)
            ELSEIF NPARTS (B12) = 0
             PULL from F out of SC1 at (1)
            ELSEIF NPARTS (B122) = 0
             PULL from F out of SC1(1) at (1)
            ELSEIF NPARTS (B123) = 0
             PULL from F out of SC1(1) at (1)
            ELSE
             Wait
            ENDIF;
OUTPUT RULE: !TO PUSH BOBBIN TO THE CORRECT PLACE
            IF BE111 = 1
             PUSH C to B11,E to BUFE11
            ELSEIF BE112 = 1
             PUSH C to B112,E to BUFE112
            ELSEIF BE113 = 1
             PUSH C to B113,E to BUFE113
            ELSEIF BE121 = 1
             PUSH C to B12,E to BUFE12
            ELSEIF BE122 = 1
             PUSH C to B122,E to BUFE122
            ELSEIF BE123 = 1
             PUSH C to B123,E to BUFE123
            ELSE
             Wait
            ENDIF;
REPORTING: Individual;
SHIFT: Undefined,0,0;

END L1
```

Rules for Loading (cont.)

```
U1

NAME OF MACHINE: U1;
QUANTITY: 1;
TYPE: Single;
PRIORITY: Undefined;
LABOR:
  Repair: None;
END
LABOR:
  Cycle: BOB;
  Pre-empt level: None;
END
DISCRETE LINKS :
      Fill: None
END
DISCRETE LINKS :
      Empty: None


END
CYCLE TIME: 2.0;
BREAKDOWNS: No;
ACTIONS, Finish
Add
  ludo1 = 0
  stage1 = 1
End Actions
INPUT RULE: !TO REMOVE EMPTY BOBBIN
           IF NPARTS (B11) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE11
           ELSEIF NPARTS (B112) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE112
           ELSEIF NPARTS (B113) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE113
           ELSEIF NPARTS (B12) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE12
           ELSEIF NPARTS (B122) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE122
           ELSEIF NPARTS (B123) = 0 AND ludo1 = 1 AND ISTATE (L1) = 1
            PULL from E out of BUFE123
           ELSE
            Wait
           ENDIF;
OUTPUT RULE: PUSH to SC1 at (1);
REPORTING: Individual;
SHIFT: Undefined,0,0;

END U1
```

Rules for Unloading.

```
NAME OF CONVEYOR: SC3;
QUANTITY: 1;
TYPE: Queuing;
PART LENGTH: 3;
MAX CAPACITY: 3;
INPUT RULE: Wait;
OUTPUT RULE: IF NPARTS (SC4) = 0
              PUSH to SC4 at Rear
             ELSEIF ISTATE (L4) = 1 AND ISTATE (U4) = 1
              PUSH to SC4 at Rear
             ELSE
              Wait
             ENDIF;
CYCLE TIME: 0.0833;
BREAKDOWNS: No;
PRIORITY: Undefined;
LABOR:
  Repair: None;
END
REPORTING: Individual;
SHIFT: Undefined;

END SC3

C4

NAME OF CONVEYOR: C4;
QUANTITY: 1;
TYPE: Queuing;
PART LENGTH: 6;
MAX CAPACITY: 6;
INPUT RULE: Wait;
OUTPUT RULE: PUSH E to BE_OUT;
CYCLE TIME: 0.0833;
BREAKDOWNS: No;
PRIORITY: Undefined;
LABOR:
  Repair: None;
END
REPORTING: Individual;
SHIFT: Undefined;

END C4
```

Rules for Conveyor.

```
NAME OF SHIFT: WEEK;
TYPE OF SHIFT: main;
OFFSET:
  Working time: 0.000000;
  Rest time: 0.000000;
SHIFT DATA: 0.000000,360.000000,0.000000
  MTWT
  MTWT
  MTWT
  MTWT
  FRIDAY
  MTWT
  MTWT
  MTWT
  MTWT
  FRIDAY
  MTWT
  MTWT
  MTWT
  MTWT
  FRIDAY
  MTWT
  MTWT
  MTWT
  MTWT
  0.000000,15.000000,0.000000
  330.000000,15.000000,0.000000
  0.000000,15.000000,0.000000
  330.000000,15.000000,0.000000
  0.000000,15.000000,0.000000
  330.000000,15.000000,0.000000
  0.000000,2880.000000,0.000000;
REPORTING: Yes;

END WEEK

FRIDAY

NAME OF SHIFT: FRIDAY;
TYPE OF SHIFT: sub shift;
OFFSET:
  Working time: 0.000000;
  Rest time: 0.000000;
SHIFT DATA: SHIFTA
  SHIFTB
  SHIFTC
  0.000000,2880.000000,0.000000;
REPORTING: Yes;

END FRIDAY
```

Rules for Shift.

Appendix C

List of Companies Visited.

1. Mazak Machine Tools, Yamazaki Machinery, Ltd.
Worcester (6 August 1992)

The Company

The plant in Worcester was set up with an initial investment of £35 millions and began production in 1987. It is based upon factory automation and flexible manufacturing system concepts which had been previously implemented in and outside Japan. It consists of rotational and prismatic machining, sheet metal processing and CIM technology to enable unmanned machining for up to 60 hours. The plant has a production staff of 240 people and the production capacity is over 100 CNC machines per month.

The FMS Set-up

The FMS consists of the following discrete modules:

The large prismatic line
Large prismatic parts such as machine beds are machined on three travelling column machining centres, each equipped with an 80 tool magazine. Fixtures and workpieces are held in 36 stored pallets, which are transferred automatic rail guided cart. Pallets are identified automatically at the time of fixturing by the scheduling computer.

The small prismatic line
Components for the gearboxes, etc. are machined on seven horizontal machining centres. Two tier pallet stacker feeds the components via automotive stacker crane.

The rotational parts line
Three mill centre lathe utilising a programmable C-axis and driven tooling are used to machine rotational parts.

The tool preset and automatic tool distribution highway

Preset tools required are identified on the CPU (MicroVax) for selection and delivery on the tool distribution highway. The highway carries tools on an overhead monorail using random access order to replenish tools directly into all machining centres and lathes and to return worn tools.

Quality control and superfinishing

Using high accuracy CNC grinding and jig boring machines, roundness and precision can be controlled to levels of less than 0.5 micron. This is achieved in a closely controlled-temperature environment, to within ± 1 °C.

The sheet metal working hall

Fully computer-controlled laser path cutting machines perform the sheet metal working.

The automated warehouse

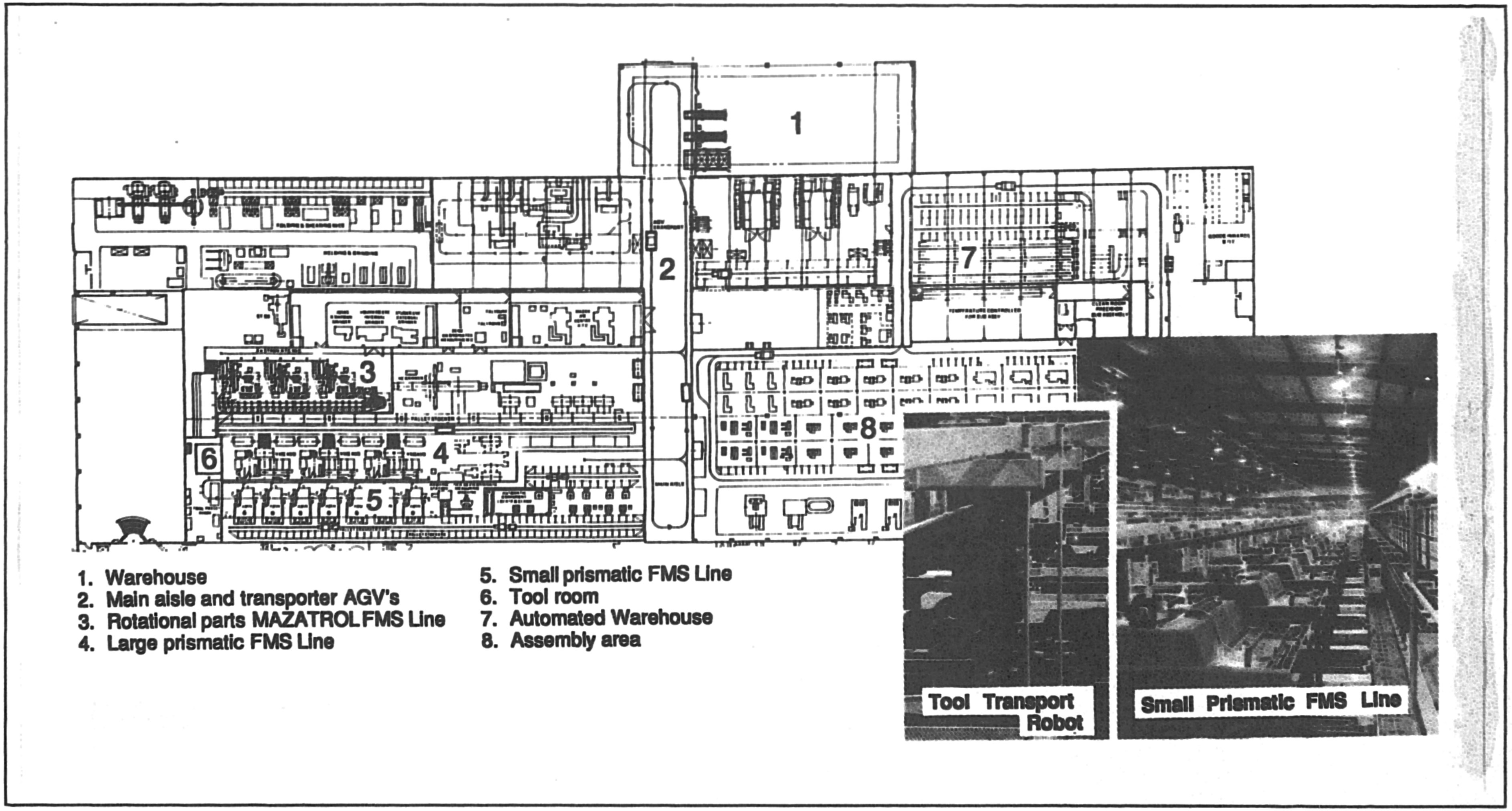
The parts loading centre controls the passage of work from the machining to assembly departments. Under central computer control, machined parts, purchased goods and assembled units are held in an automatic warehouse and distributed to the assembly areas using two AGV transporter trucks.

The assembly hall

Machine beds, sub-assemblies and bought in components are all delivered to the assembly area by transporter AGVs. Machine assemblies, including spindle units, tool magazines and control systems are all subjected to exhaustive run and test procedures for 24 hours prior to final assembly.

The FMS hardware and software control system

A central IBM S/38 system for production and scheduling information control is connected to three DEC Micro VAX FMS-CPU's which control the on-line systems. All FMS lines are controlled by the latest production management software from the moment the raw materials enter the factory to the despatch of the finished product.



Mazak Machine Tool Plant Layout.

2. Denford Machine Tool Ltd, Brighouse, West Yorkshire. (12.8.92)

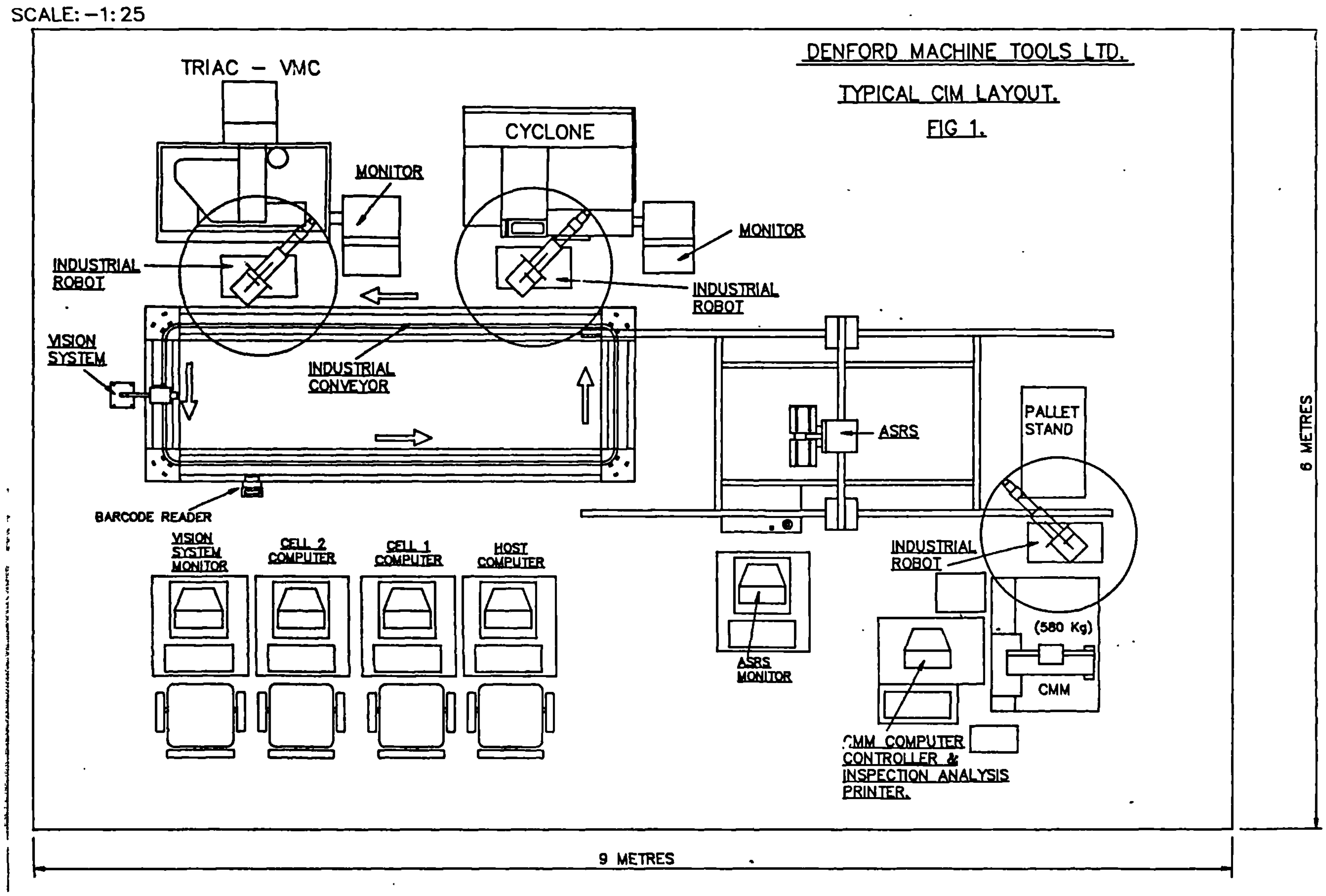
The company

Established thirty years ago, Denford Machine Tools Limited is a manufacturer of machine tools which range from desk-top DNC and CNC machines to larger CNC lathes, milling machines and machining centres for advanced training and production applications. The company has also developed and marketed software products and provided turnkey solutions which incorporate Computer Integrated Manufacturing (CIM) technology.

The Denford FMS (educational)

The FMS developed is modular in design and can range in size from a cell (lathe + robot, mill + robot, or lathe + mill + robot) to a full scale system by integrating the cells with material handling system, storage and retrieval configurations (AS/RS) and inspection station (CMM). The entire system is governed by the supervisory software (developed in-house) in conjunction with the cell controller which sequence and monitor the performance of all operations within the system. Three different modes of operation are available through the software: manual operation which allow the operator to step the component through the system from start to finish checking, simulation which shows the full manufacturing cycle, and automatic mode which runs the system through the completed automatic cycle.

For maximum flexibility each cell controller can control up to one robot and two individual machines. Cell controllers can be networked to expand the systems allowing the cells or system to be under total control from the host computer.


SCALE:-1:25
DENFORD MACHINE TOOLS LTD.
TYPICAL CIM LAYOUT.
TRIAC - VMC
CYCLONE
MONITOR
MONITOR
INDUSTRIAL ROBOT
INDUSTRIAL ROBOT
VISION SYSTEM
INDUSTRIAL CONVEYOR
ASRS
PALLET STAND
BARCODE READER
VISION SYSTEM MONITOR
CELL 2 COMPUTER
CELL 1 COMPUTER
HOST COMPUTER
ASRS MONITOR
INDUSTRIAL ROBOT
(580 Kg)
CMM
CMM COMPUTER CONTROLLER & INSPECTION ANALYSIS PRINTER.
9 METRES
6 METRES
FIG 1.

3. JCB Transmissions, Wrexham. (13.8.92)

The Company

JCB Transmissions is a subsidiary of the private company JCB Excavators of Rochester. JCBT was established in 1978 to produce transmissions for the parent company when outside contractors could not supply transmissions to a high enough standard. The company produces custom designed axles and gearboxes for excavators and on/off highway vehicles. The majority of the products go to JCBE and about 7-8 % are sold to original equipment manufacturers.

The JCB Flexible Manufacturing Systems

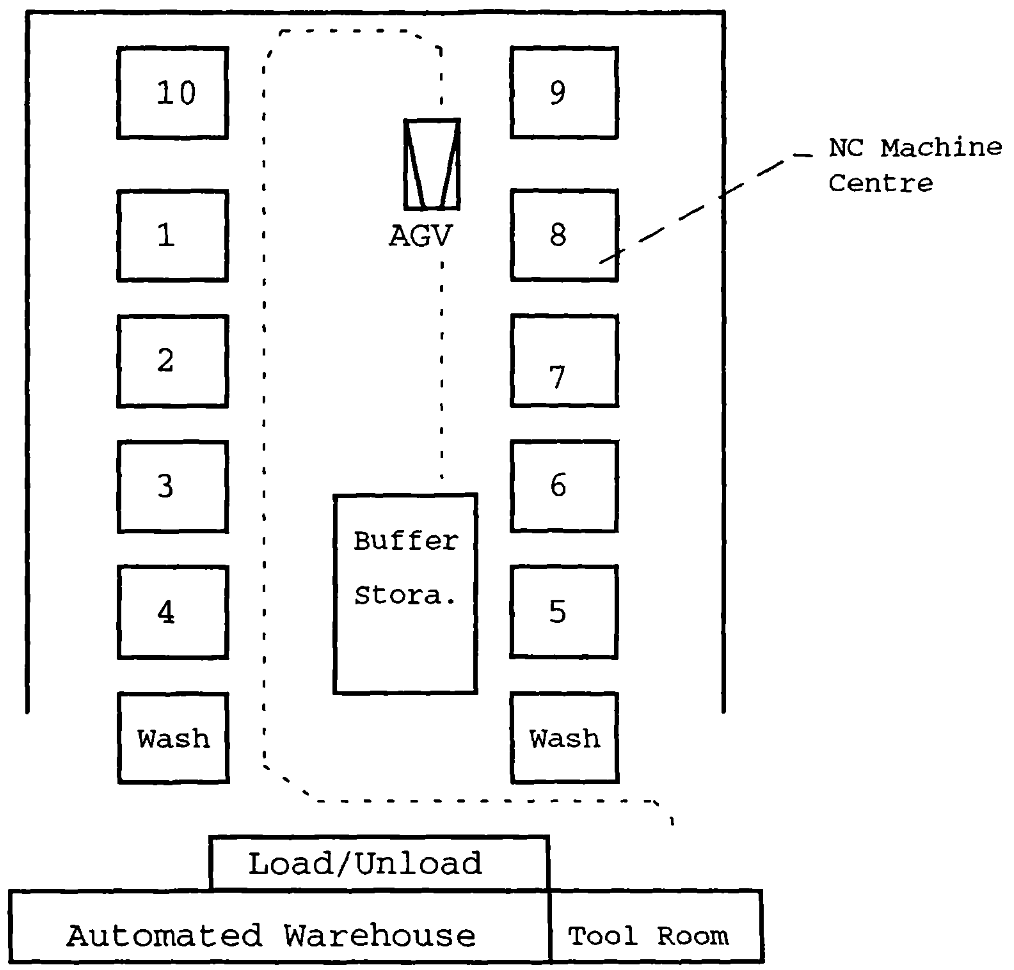
The flexible manufacturing system was introduced in 1985 with an investment of £6.5m in an effort to increase the productivity of the company. This objective has been achieved by the reduction in the gear box machining time by 25% and an increase in daily production by 50%.

The FMS consists of ten Scharmann Solon 2.3 machining centres with Siemens control system, two Beyss CNC washing machines and one LK co-ordinating measuring machine. The transport system consists of twelve Rolatruc AGVs, linking the FMS to a high rise automated warehouse.

System control is via 6 DEC PDP-11 and microvax computers and Siemens PLCs. The FMS machines 28 high value prismatic parts. A computerised management system keeps track of the movement of parts.

Although the system was designed to run 24 hours a day, utilising two 8 hour manned shifts and two 4 hour unmanned shifts, it has only been run unmanned for a maximum of 1.5 hours.

A computerised tool management system, ISIS Toolware is used to handled the huge amount of tools needed during the FMS operation (3000 cutting tools, 2000 gauges, 500 jigs and fixtures, and 100 special tools.



4. Liverpool University Flexible Manufacturing System

The FMS at the University of Liverpool was developed in 1985 in the Advanced Manufacturing Systems and Technologies Laboratory. The main purpose for the set-up is for teaching and research on factory automation. The system is in modular form and consists of three cells, namely machining cell, materials handling cell and product assembly cell.

Materials Handling Cell

The material handling cell consists of a conveyor and a Puma 560 industrial robot employing VAL II software. The conveyor has four load/unload stations. Workpieces are held in pallets that move along the conveyor between the stations. Each station has a sensor to monitor the position of the pallets.

Machining Cell

The machining cell consists of a Denford CNC milling machine and lathe operating on ISO format. An industrial prosthetic robot (Yaskawa Motoman L3) is used to move material through the machining cell to and from the roller conveyor system. The robot is mounted on a piston driven conveyor system which allows bi-directional movement of the robot.

Assembly Cell

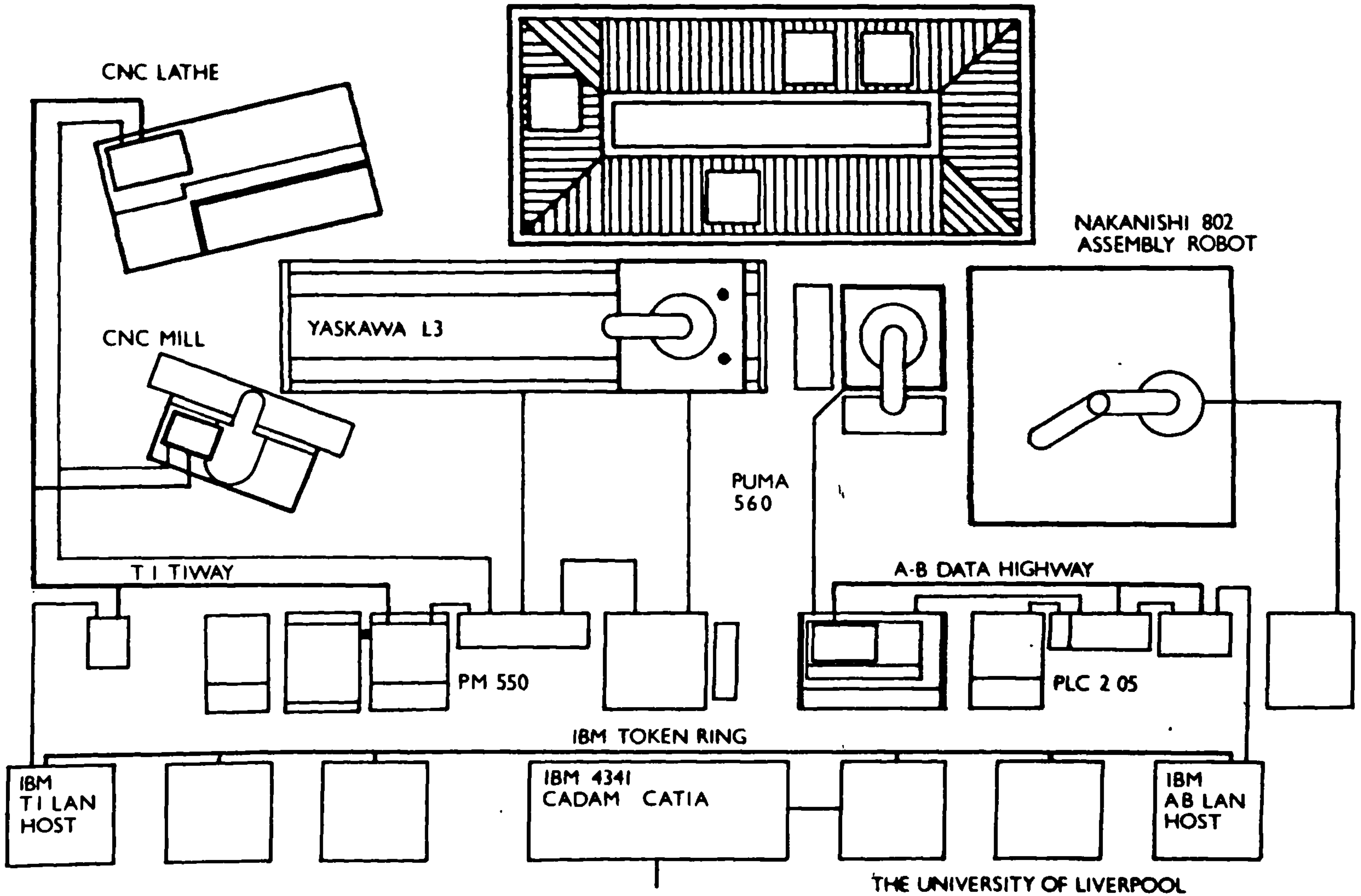
The assembly cell consists of a Nakanishi 802 scara type robot, mounted on a rigid table which incorporates several built-up jigs to ensure correct alignment of individual items during assembly. The robot is used to perform assembly tasks through the use of either teach or manual data input modes.

Control System

The FMS uses two separate controllers to sequence the events of the different cells. The Texas Instrument TI 525 logical controller is used to control the events occurring in the machining cell, i.e., the NC machines and the Yaskawa robot, together with the sequencing of movement of the Yaskawa robot between its three stations. The sequencing of the movement of the pallets on the roller conveyor and the movement of the Puma robots are controlled via the Allen Bradley PLC 2/05 programmable logic controller.

Communications Link

Two types of local area networks (LANs) are used to achieve communication between a host computer and its secondaries such as PLC's and the CNC machines. These are Texas Instrument TIWAY and Allen Bradley Data-Highway.



THE UNIVERSITY OF LIVERPOOL
FLEXIBLE MANUFACTURING SYSTEM

Appendix D

Manufacturing System Design Questionnaire

THE UNIVERSITY
of LIVERPOOL

Department of Industrial Studies

Liverpool
L69 3BX

Telephone Direct:
0151 794
Telephone Secretary:
0151 794 4681/2
Facsimile: 0151 794 4693

April 1994

Dear Sir/Madam,

Re: Design of Manufacturing System Questionnaire

A research work on the methodologies and tools to support manufacturing system design is being carried out at the Department of Industrial Studies, University of Liverpool.

The purpose of this survey is to get an overview of the practice of manufacturing system design within the metal goods and engineering industries in the UK.

Your cooperation is solicited in filling the questionnaire on behalf of your company /site. Please pass the questionnaire on to the more appropriate member(s) of your organisation if you do not feel comfortable to complete it.

The information provided will be treated as strictly confidential.

A high response rate is vital for the success of this study. We would be delighted to answer any query regarding the questionnaire. Please return the completed questionnaire using the enclosed envelope.

We would like to thank you for your time and assistance.

Yours sincerely,

(M. Razali)

MANUFACTURING SYSTEM DESIGN QUESTIONNAIRE

*A **Manufacturing System** is a complex arrangement of physical elements such processing equipment, material handling system, and computer control systems whose purpose is to achieve economic product manufacture, measured by parameters such as throughput time, inventory, percentage defective, percentage on-time delivery and unit cost.*

*This survey is concerned with the **design of the physical system** of Manufacturing System, i.e., the complex arrangement of the physical elements **for piece part** production.*

PLEASE NOTE!

ALL questions refer to the manufacturing system ON SITE.

To complete this questionnaire, you are just required to TICK the boxes, and write in the spaces provided. You may TICK more than once where applicable.

SECTION A : Information on the current Manufacturing System

1. What category of business would you describe your company (on site) is involved in?

- ☐ Mechanical engineering
- ☐ Manufacture of office machinery and data processing software
- ☐ Electrical and electronics engineering
- ☐ Manufacture of motor vehicles and parts thereof
- ☐ Manufacture of other transport equipment
- ☐ Instrument engineering

2. What major manufacturing functions are performed within the manufacturing system? *(Please TICK)*

☐ Prismatic part machining	☐ Cylindrical part machining
☐ Inspection	☐ Material handling
☐ Assembly	☐ Others : (please specify)

3 How many types or families of parts/products are produced in the manufacturing system annually?

☐ less than 5	☐ 6 - 10	☐ 11 - 20
☐ 21 - 50	☐ 51 - 100	☐ 101 - 200
☐ more than 200	☐ Others: (please specify)__________	

4 What is the average production rate (parts per hour) for a typical part family?

☐ less than 1 ☐ 1 - 10 ☐ 11 - 50
☐ 51 - 100 ☐ more than 100
☐ Others: (please specify) ____________

5 What is the average range of batch sizes of parts capable of being produced in the manufacturing system?

Minimum of _____________ to a Maximum of _____________

6 Are the products manufactured :
☐ to stock
☐ to order
☐ both.

7 How would you describe the development of the Manufacturing System in your company? ***Please Tick in the box provided. If relevant, more than one box may be ticked.***

☐ From semi-automatic/automatic machines to CNC.
☐ Moving froni stand alone CNC to integration with CAD/CAM
☐ From CNC into cellular layout (Flexible Manufacturing Cell)
☐ From cellular layout (Flexible Manufacturing Cell) into multi-machine/multi-cell Flexible Manufacturing System
☐ Starting with computerised manufacturing information system (e.g. MRPII) and linking engineering data to production, purchasing, sales, etc.
☐ Automating the materials flow with automated material handling, and then linked to the machine tools
☐ Initiating a totally greenfield site into FMS
☐ Others:(please specify) ________________________________

8 Do you consider your manufacturing system belong to any one of the following category?
☐ Transfer line ☐ Dedicated flow line
☐ Flexible manufacturing system ☐ Manned flexible cell
☐ Unmanned flexible cell ☐ Job shop
☐ Others (please specify) ____________________________________

9 For the system with materials handling system, what type of material handling system is used?

- ☐ Manual
- ☐ Automated guided vehicle
- ☐ Conveyors
- ☐ Robots
- ☐ Gantry loaders
- ☐ Rail guided transfer mechanism
- ☐ Automatic Storage/Retrieval System
- ☐ Others (please state):

____

10. How was your Manufacturing System developed?

- ☐ Developed using turnkey system
- ☐ Integrated in-house

11. What is the automation level of your manufacturing system? ***Please state approximate percentage.*** (e.g. Processing equipment: Manual =0%; Semi-automatic = 25%; Fully automatic = 75%)

	Manual	Semi-automatic	Fully automatic
Processing equipment			
Materials handling			
Information flow			

12. What are the relative costs of implementing the following system components? ***(Please give approximate percentage)***

	< 10 %	10 - 25 %	25 - 50 %	50 - 75 %	> 75 %
Machining equipment					
Material handling equipment					
Inspection equipment					
Information and computer networks					
Others (Please state):					

13. What approach is used for system justification?

☐ Economic ☐ Strategic ☐ Both

14. For economic evaluation, what method is used?

☐ Payback ☐ Return On Investment

☐ Internal Rate of Return ☐ Net Present Value

☐ Others (please state) ______________________________

15. If strategic system justification is carried out, briefly explain how:

____

16. What is the measure of the manufacturing systems capacity? ____________

17. How would you consider the performance of the manufacturing system, with respect to the following. *Circle appropriate number, 1 = very poor, 5 = very good.*

• Lead time reduction	1	2	3	4	5
• Through-put time reduction	1	2	3	4	5
• Work-in-progress reduction	1	2	3	4	5
• Manufacturing cost reduction	1	2	3	4	5
• Product quality improvement	1	2	3	4	5
• Machine utilisation improvement	1	2	3	4	5
• Flexibility improvement	1	2	3	4	5
• Others (Please state):					
______________________	1	2	3	4	5
______________________	1	2	3	4	5

SECTION B: Manufacturing system design methodologies and techniques

1. Does the company have a specific and clear manufacturing strategy?

☐ YES ☐ NO

2. What are the strategic objectives to be achieved in the manufacturing system design/redesign? And what are their relative importance to the company? *Please TICK box and circle appropriate number; 1= least important, 5 = most important.*

☐ Cost	1	2	3	4	5
☐ Quality	1	2	3	4	5
☐ Flexibility	1	2	3	4	5
☐ Delivery	1	2	3	4	5

3. Which aspect of delivery are you concerned with?
   - ☐ Speed
   - ☐ Reliability
   - ☐ Both

4. Which <u>aspects of flexibility</u> were you concerned with? ***(Please TICK)***

   - ☐ Volume flexibility
   - ☐ Product flexibility
   - ☐ Expansion flexibility
   - ☐ Process flexibility
   - ☐ Machine flexibility
   - ☐ System flexibility
   - ☐ Others (please state):

   ____

5. What <u>approach(es) is(are)</u> taken to achieve the desired flexibility:

   - ☐ Use of flexible machines
   - ☐ Improve flexibility of material handling
   - ☐ Improve machine control flexibility
   - ☐ Increase tooling capacity
   - ☐ Having flexible routing/scheduling
   - ☐ Adopting Cellular system
   - ☐ Introduce multiskill/multidisciplinary workers
   - ☐ Others (please specify)

   ____

6. <u>How often</u> do you design/redesign your manufacturing system?
   - ☐ Every new product introduction
   - ☐ Every time with major product modifications
   - ☐ Every huge change in production volume (of the same product)
   - ☐ When improvement in technology is necessary
   - ☐ Others (please state): ____________________________

7. What is the <u>average lead time</u> (man-month) for manufacturing system design?
   - ☐ 1 - 3 man-months
   - ☐ 4 - 6 man-months
   - ☐ 6 - 12 man-months
   - ☐ more than 12 man-months
   - ☐ Others: ____________________

8. What percentage of time is spent in each of the manufacturing system design stage?
Give approximate percentage.

	Approximate percent
Requirements analysis	[ ]
Conceptual design	[ ]
Detailed design	[ ]
Evaluation and selection	[ ]

9. <u>Who</u> are involved in the design of the manufacturing system? And what is the nature of involvement? ***Please TICK and fill in the spaces.***

	Nature of involvement
☐ Manufacturing department	______________________
☐ Industrial Engineering department	______________________
☐ Product design department	______________________
☐ Marketing department	______________________
☐ Engineering department	______________________
☐ Quality control department	______________________
☐ Computer systems departmen	______________________
☐ Equipment suppliers	______________________
☐ Customers	______________________
☐ Others (Please state)	______________________

10. How significant is the influence of customers on the manufacturing system design?

☐ Very significant ☐ Some significant ☐ none

11 How familiar are you with any of these techniques? **(Please tick)**

Techniques	Familiar and used	Familiar but not used	Not familiar
SADT			
Data flow diagram			
IDEF			
GRAI methodology			
Input-output diagram			
Spreadsheet			
Group Technology			
Simultaneous Engineering			
Graphical simulation/modelling			
Artificial intelligence			
Operations Research			

12. Are you using those methodologies/tools in the various stages of manufacturing system design? ***Please TICK in the appropriate spaces.***

	Requirements analysis	Conceptual design/specification	Detailed design	Technical Evaluation and selection
SADT				
Data Flow Diagram				
IDEF				
GRAI Methodology				
Input-output diagram				
Node tree analysis				
Group Technology				
Spreadsheet				
Simultaneous Engineering				
Graphical simulation				
Mathematical Simulation				
Artificial intelligence				
Quality Function Deployment				
Others (Please state):				

13. How helpful do you find those methodologies/tools have been?
Please TICK in the appropriate spaces.

	Facilitate design process and improve design time	Did not affect design process and design time	Worsen design process and lengthen design time
SADT			
Data Flow Diagram			
IDEF			
GRAI Methodology			
Input-output diagram			
Node tree analysis			
Group technology			
Spreadsheet			
Simultaneous Engineering			
Graphical simulation			
Mathematical Simulation			
Artificial intelligence			
Quality Function Deployment			
Others (Please state):			

14. How is INTEGRATION achieved?
☐ through materials flow ☐ through information flow ☐ both

15. Are you using ISO Open System Interconnection for computer communication?

☐ YES ☐ NO

16. If NO, what others are you using? ____________________________

17. What type of communication network configuration are you using?
- ☐ single-tier control hierarchy (DNC)
- ☐ multi-level control hierarchy with point-to-point communication (CNC)
- ☐ multi-level control hierarchy with local area network
- ☐ non-hierarchical control structures
- ☐ Others (please state) ____________________________________

18. What are the major constraints during the design and development of the physical system of the Advanced manufacturing System ? ***(Please TICK)***
- ☐ Objectives not clearly stated
- ☐ Systems requirements poorly specified
- ☐ Insufficient internal skill
- ☐ Lack of top management support
- ☐ Lack of planning and design tools
- ☐ Organisational and personal related problems
- ☐ Others (please state) ____

19. Based on your experience, what are your suggestions for the development of robust methodology for the design of Advanced Manufacturing Systems?

____

____

BACKGROUND INFORMATION

About you:
Job title: ____________________________
Department: ____________________________

About the company:
Name of company: ____________________________
Annual turnover: ____________________________

Number of employees: ____________________________

Would you like to receive a concise summary of the result from the survey? ☐ YES ☐ NO

Thank you very much for your time and kind co-operation. Please ensure that you answer as many questions as possible. For analysis purposes, please return the questionnaire even if your company is not engaged in Advanced Manufacturing System.

Appendix E

Standard Industrial Classifications

Standard Industrial Classifications; major divisions

The standard industrial classification (SIC) is a categorisation of the industries that provide goods and services in the United Kingdom. The classification is produced by the Central Statistical Office and provides a useful framework for analysing the British economy.

The industries are categorised into nine divisions:

0 Agriculture, forestry and fishing.
1 Energy and water supply industries.
2 Extraction of mineral and ores other than fuels; manufacture of metals, mineral products and chemicals.
3 Metal goods, engineering and vehicle industries.
4 Other manufacturing industries.
5 Construction.
6 Distribution, hotels and catering; repairs.
7 Transport and communication.
8 Banking, finance, insurance, business services and leasing.
9 Other services.

The postal survey described in Chapter 4 focused on division 3, which includes the following activities:

32 Mechanical engineering.
33 Manufacture of office machinery and data processing software.
34 Electrical and electronic engineering.
35 Manufacture of motor vehicles and parts thereof.
36 Manufacture of other transport equipment.
37 Instrument engineering.

Appendix F

Scales of Measurement for Multiple Criteria Problems

PRIORITY AND WEIGHT

In multiplecriteria problems ranking is necessary in order to determine the relative importance of each of the criteria. The relative importance of criteria may be expressed in terms of priority or weight. *Priority* refers to the case where the criteria are ordered according to importance and unless the higher level criteria is taken into consideration, the next one does not come into play. *Weights* are attached to differentiate the relative importance of several criteria with the same priority.

Scales of Measurement

Nominal scales

Numbers are used merely as labels, for example as a form of identification of the entities. They do not indicate the relative properties of the entities. These scales are least restrictive as well as least informative of all.

Ordinal scales

These are purely ranking scales. Elements are distinguished according to a single criterion. The difference between the preference between two elements are not known directly from the ordinal measurement.

Interval scales

These have constant units of measurement. A very common example is the Fahrenheit scale of temperature measurement. The zero point of Fahrenheit scale is not natural. An object A at 50°F and another object at 100 °F does not mean that B is twice as hot as A, but it can be said that B is hotter than A by 50 degrees.

Ratio scales

Measurements of length, weight, volume speed, height are examples of ratio scales. These have a natural zero and a constant unit of measurement.

The ratio scale provide the most information of all. The ordinal scale provides more information than the nominal scale but less than the interval scale. Loosely termed, the nominal and ordinal scales are categorical or qualitative scales while the interval and ration scales are quantitative scales of measurement.

In multiple criteria decision making, the ranking of the various criteria is necessary and the criterion for ranking is based on the deemed 'importance' of the objectives.

Tabucanon, M.T. (1988)
Multiple criteria decision making in industry, Elsevier, Amsterdam.
[ISBN 0-444-70541-4]

Appendix G

Analytic Hierarchy Process (AHP)

1 Introduction

Analytic Hierarchy Process (AHP) [226] is a multi criteria decision making (MCDM) model which enables decision makers represent the interaction of multiple criteria in complex and unstructured situations. The technique is based on the principle that, to make decisions, experience and knowledge of people is at least as valuable as the data they use. Decision applications of the AHP are carried out in two phases: (1) *hierarchic design* which requires experience and knowledge of the problem area, and (2) *evaluation* which is based on the concept of paired comparisons, where the elements in a level of the hierarchy are compared in relative terms as to their importance or contribution to a given criterion that occupies the level immediately above the elements being compared.

The theory is based on the following axioms [109, 226]:

1) *Reciprocal Comparison.* The decision maker must be able to make comparisons and state the strength of his preferences. The intensity of these preferences must satisfy the reciprocal conditions: If A is x times more preferred that B, then B is $1/x$ times more preferred than A.
2) *Homogeneity.* The preferences are represented by means of a bounded scale.
3) *Independence.* When expressing preferences, criteria are assumed independent of the properties of the alternatives.
4) *Expectations.* For the purpose of making a decision, the hierarchic structure is assumed to be complete.

The advantage of using AHP is that it can overcome the problem of managers having to make ad hoc decisions on alternatives in the operations management area. The technique has found widespread applications in economic/management problems, political and social, as well as technological problems [109]. Within the production and operations management decision hierarchies have been suggested in the following areas: product design decisions, plant layout design decisions, preventive maintenance frequency selection, choice of logistic carrier, facility location planning, supplier selection decision, choice of technology and time series forecasting adjustments [208], performance evaluation of manufacturing systems [9], selection of automated manufacturing systems [186].

2 Hierarchic Design

1) The technique starts with stating the goal or objective to be achieved in the decision making exercise. This will be at the top of the decision making hierarchy.
2) The next level consists of criteria or factors that may have impact on the objective. These factors may be grouped into various categories such as strategic, technological, economic and social. For each of the categories, identify the criteria, C, where, C_i, $1 \le i \le m$.
3) List the set of alternatives (A_i, $1 \le i \le n$) which the organisation can undertake.
4) Develop a graphical representation of the problem in terms of the overall goal, factors, criteria, and the decision alternatives. Such a graph depicts the hierarchy for the problem, Figure G1.

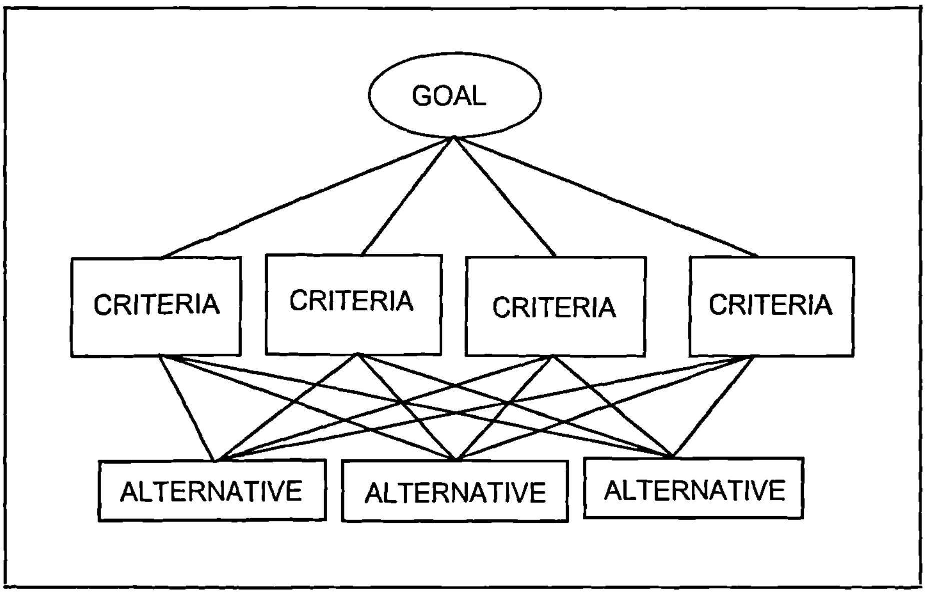


Figure G1 Decision making hierarchy

3 Evaluation

1) Assign weights to each alternative on the basis of the relative importance of its contribution to each decision criterion. This is carried out through pairwise comparison of the alternatives based on the decision criterion. Table G1 shows a typical scale for pairwise comparison which may be used for preparing the pairwise matrix M^k for each criterion C_k (where M^k_{ij} is evaluated when alternative A_i is compared with the alternative A_j). Table G2 shows the general format of a pairwise comparison matrix (M^k).
2) Once the pairwise comparison matrix has been formed for a criterion C_k, the normalised priority for each alternative is synthesised. This is done as follows:

- Sum the values in each column of M^k.
- Divide each element in the column by its column total which results in a normalised pairwise comparison matrix.
- Compute the average of the elements in each row of the normalised comparison matrix thus providing an estimate of the relative priorities of the n alternatives. This results in a priority vector PM^k for each criterion C_k where PM^k_i denotes the priority for alternative A_i with respect to criterion C_k.

Degree of preference	Definition
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred
2,4,6,8	Intermediate preferences between the two adjacent judgements.
Reciprocal of the above non-zero numbers	If criterion $i(C_i)$ is assigned one of the above non-zero numbers when it is compared with criterion j $(C_j)C_j$ has the reciprocal value when it is compared with C_i.

Table G1 Scale for pairwise comparison.

Evaluation criteria	C_1	C_2	C_3	C_m
C_1	1			
C_2	C_2/ C_1	1		
C_3	C_3/ C_1	C_3/ C_2	1	
C_m	C_m/ C_1	C_m/ C_2	C_m/ C_3	1

Table G2 Format of pairwise comparison matrix.

3) In addition to the pairwise comparison of the n alternatives, use the same pairwise comparison procedure to set priorities for all the criteria in terms of the importance of each in contributing towards the overall goal of the organisation. Let L_{ij} denote each element of the resulting pairwise comparison matrix, when C_i is compared with C_j.
4) The priority vector PL is synthesised similar to step (2) (PL_i denotes the priority for criterion C_i).
5) Calculate the overall priority for alternative A_i denoted by P_i as follows:

$$P_i = \sum_{K=1} PM^k_i \ * PL_k \qquad \text{.................................(i)}$$

6) Choose the alternative which has the highest priority.

7) Checking the Consistency of Judgements. Decision makers are rarely consistent in their judgements with respect to qualitative issues. The AHP technique incorporates such inconsistencies into the model. A consistency ratio, CR, is driven from the ratio of the consistency of the results being tested to the consistency of the same problem evaluated with random numbers.

If λ_{max} is the largest eigenvalue of the matrix M, then, $\lambda_{max} \geq n$, where $\lambda_{max} = n$ holds for the perfectly consistent case only. A consistency index, CI, is now defined as

$$CI = (\lambda_{max} - n)/(n - 1) \qquad \text{................................(ii)}$$

which is zero in the perfectly consistent case. To assess the consistency in the above equation, it is compared to the worst case that will be the case of pairwise comparison matrix whose entries are filled at random. doing it for many samples and for various matrices. Values have been obtained and is shown in Table G3 [226].

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table G3 Values of Random Index, RI, for different matrix sizes, *n*.[Saaty, 1980]

n represents the dimension of the matrix and RI is the random index evaluated through equation (2) for these random matrices. Consistency ratio, CR, is defined as

$$CR = CI/RI.$$

For acceptable results, i.e., pairwise comparison has been consistent, CR should be less than 0.10 (10%).

4 Example of Priority Calculations

Consider the case where the pairwise comparison of the competitive advantages of price, quality, delivery reliability, delivery speed, product flexibility and volume flexibility to be as shown in Table G4.

With respect to meeting the business objective, price is considered to be slightly more important than quality, so a value of 2 is placed in the price/quality location and 1/2 in quality/price location. When price is considered to be extremely important when compared to delivery speed, a value of 9 is placed in price/delivery speed location. In situation where both elements have the same degree of importance, a value of 1 is placed in the appropriate locations.

The matrix formed is called the pairwise comparison matrix, M1.

	Price	Quality	Delivery reliability	Delivery speed	Product variety	Volume changes
Price	1	5	7	9	9	7
Quality	1/5	1	3	3	2	1
Delivery reliability	1/7	1/3	1	2	3	2
Delivery speed	1/9	1/3	1/2	1	1	2/3
Product variety	1/9	1/2	1/3	1	1	2/3
Volume changes	1/7	1	1/2	3/2	3/2	1

The total for each column in matrix M1 is then evaluated:

	1.708	8.167	12.333	17.500	17.500	12.333

Matrix M1 is normalised by dividing each element in a column by the sum of the column. To obtain the principal vector M2, the values in each row are totalled in the Sum column and each sum is averaged.

	Normalised Column						Sum	Sum/6
Price	0.585	0.612	0.568	0.514	0.514	0.568	3.361	0.560
Quality	0.117	0.122	0.243	0.171	0.114	0.081	0.848	0.141
Delivery reliability	0.084	0.041	0.081	0.114	0.171	0.162	0.653	0.109
Delivery speed	0.065	0.041	0.041	0.057	0.057	0.054	0.315	0.053
Product flexibility	0.065	0.061	0.027	0.057	0.057	0.054	0.321	0.054
Volume flexibility	0.084	0.122	0.041	0.086	0.086	0.081	0.500	0.083
	1.000	1.000	1.000	1.000	1.000	1.000	6.000	1.000

From the principal vector the order of priority (in percentages) for the competitive advantages is: Price = 56, Quality = 14, Delivery reliability = 11, Volume flexibility = 8, Product flexibility = 5, and Delivery speed = 5.

5 Checking the consistency of judgements.

Define matrix M3 where M3 = M1 * M2, and M4 where M4 = M3/M2.

$$M3 = \begin{vmatrix} 1 & 5 & 7 & 9 & 9 & 7 \\ 1/5 & 1 & 3 & 3 & 2 & 1 \\ 1/7 & 1/3 & 1 & 2 & 3 & 2 \\ 1/9 & 1/3 & 1/2 & 1 & 1 & 2/3 \\ 1/9 & 1/2 & 1/3 & 1 & 1 & 2/3 \\ 1/7 & 1 & 1/2 & 3/2 & 3/2 & 1 \end{vmatrix} \begin{vmatrix} 0.560 \\ 0.141 \\ 0.109 \\ 0.053 \\ 0.054 \\ 0.083 \end{vmatrix} = \begin{vmatrix} 3.752 \\ 0.930 \\ 0.670 \\ 0.326 \\ 0.331 \\ 0.519 \end{vmatrix}$$

$$M4 = \begin{vmatrix} 3.752 \\ 0.930 \\ 0.670 \\ 0.326 \\ 0.331 \\ 0.519 \end{vmatrix} \div \begin{vmatrix} 0.560 \\ 0.141 \\ 0.109 \\ 0.053 \\ 0.054 \\ 0.083 \end{vmatrix} = \begin{vmatrix} 6.379 \\ 6.596 \\ 6.147 \\ 6.151 \\ 6.130 \\ 6.253 \end{vmatrix}$$

The maximum or principal eigenvalue, λ_{max}, is the average of the elements of M4,

i.e., $\lambda_{max} = (6.379 + 6.596 + 6.147 + 6.151 + 6.130 + 6.253)/6 = 6.276$.

Consistency Index (CI) is a measure of deviation from consistency, and is defined as

C.I. = $(\lambda_{max} - n)/(n - 1)$, where n is 6 in this case. Hence,

C.I. = (6.276 - 6)/5 = 0.055.

From the Table of Random Index (Table G3), find the Random Index, R.I. for $n = 6$.

R.I. = 1.24.

Consistency Ratio, C.R. = C.I./R.I. = 0.055/1.24 = 0.045.

Since C.R. is less than 10%, the judgements have been consistent.