A Next Generation Manufacturing Control System for a Lean Production Environment

by

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Dedication

My wife and friend - Jillian Lee

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Most importantly I must recognise the sacrifice made by my family and their unfailing love and support throughout my years of study. I have been blessed with a remarkable wife and friend, Jillian and two fantastic boys Jason and Matthew.

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SYNOPSIS

This thesis focuses on addressing the need for a new approach to the design and implementation of manufacturing control systems for the automotive industry and in particular for high volume engine manufacture. Whilst the operational domain in the automotive industry has moved to *lean production* techniques, the design of present-day manufacturing control systems is still based on systems intended for use in a *mass production* environment. The design and implementation of current manufacturing control systems is therefore inappropriate when viewed from a business context. The author proposes that it is possible to create a more appropriate manufacturing control systems based on an optimised use of advanced manufacturing technology within the complete business context.

Literature is reviewed to provide a detailed understanding of the relationship between modern operating practices and the application of contemporary control systems. The primary tasks of manufacturing control systems, within the context of a structured systems approach to manufacturing technology, production management and industrial economics are identified. A study of modern manufacturing control system technology is carried out, highlighting the fundamental principles that influence application engineering in this area.

The thesis develops a conceptual design framework that aids the identification of attributes required of a next generation manufacturing control system (NGCS), in order to enhance the business performance of *lean* automotive manufacturing. The architecture for a next generation control system is specified and a *proof of concept* system implemented. Potential advances over contemporary practice are identified with the aid of a practical implementation at a major automotive manufacturer.

CONTENTS

List of Appendixes

List of Figures & Tables

AMT	Advanced Manufacturing Technology
BEA	Business Environment Analysis
CI	Continuous Improvement
CIM	Computers in Manufacturing
CIMOSA	Computer Integrated Manufacturing-Open Systems Architecture
CNC	Computer Numerical Control
DAI	Distributed Artificial Intelligence
DARM	Design Attribute Relationship Matrix
DCS	Design Control System
DDM	Design and Development Methodologies
DTI	Department of Trade and Industry
EBPA	Platform & Enterprise Model
EDDI	Error Diagnostic Dynamic Indicator
EN	Euro Norm.
FB	Function Blocks
GMPD	General Motors Powertrain Division
I	Hardware System Architecture
HDS	Highly Distributed Systems
HMI	Human Machine Interface
I/O	Inputs/Output
IEC	International Electrotechnical Commissions
IEE	Institute of Electric Engineers
IEEE	Institute of Electric and Electronic Engineers
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
MAP	Manufacturing Automation Protocol
MAS	Multi-agent Systems
MSFC	Machine Sequence Function Chart
MXIC	Manual Cross Interlock Checking
NC	Numerical Control
NGCS	Next Generation Controller
NPV	Net Present Value
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OMAC	Open Modular Architecture Controller
PLC	Programmable Logic Controller
PCS	Proof of Concept System
QMT & T	Quality Management Tools & Techniques
RTOS	Real Time Operating System
SCADA	Supervisory Control and Data Acquisition
SIMPLE	Sequential, Integrated Motion and Process Logic Educator
STA	Socio-technical Analysis
TOP	Technology, Organisation and People
TQM	Total Quality Management
TRA	Technical Requirements Analysis
VE	Value Engineering
YEL	Years of expected life of the system

The purpose of this section is to define the meaning of scribe a number of terms in the context of this thesis.

Architecture

The Oxford English dictionary[1] provides a number of definitions of the term *Architecture*. The most appropriate within the context of this thesis is: *The conceptual structure and logical organisation of a computer based system.* For the purposes of this thesis this definition is taken to have a broader meaning i.e. ***the manner in which elements of a specific system are organised and integrated together***, [Zwegers 1998].

Reference Architecture

This thesis reserves the term *Reference Architecture* for: ***a generic architecture serving as a point of departure for many specific architectures.***

Architectural Units

An *Architecture* is made up of a number of ***fundamental building blocks*** known in this thesis as *Architectural Units.*

Engineering Design

The systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints. [Dym 1999].

Method

The term *method* is used to define: ***the procedures or process used to construct the orderly arrangement of ideas.***

[1] Oxford English Reference Dictionary, Second Edition, Oxford University Press 1996.

Methodology

Methodology is considered to be: ***a body of methods used within a particular framework.***

Framework

The term *'Framework'* is used to describe: ***the environment within which all the stated terms, structures and methodologies are organised.***

Domain

A particular field of use within which a framework is applied.

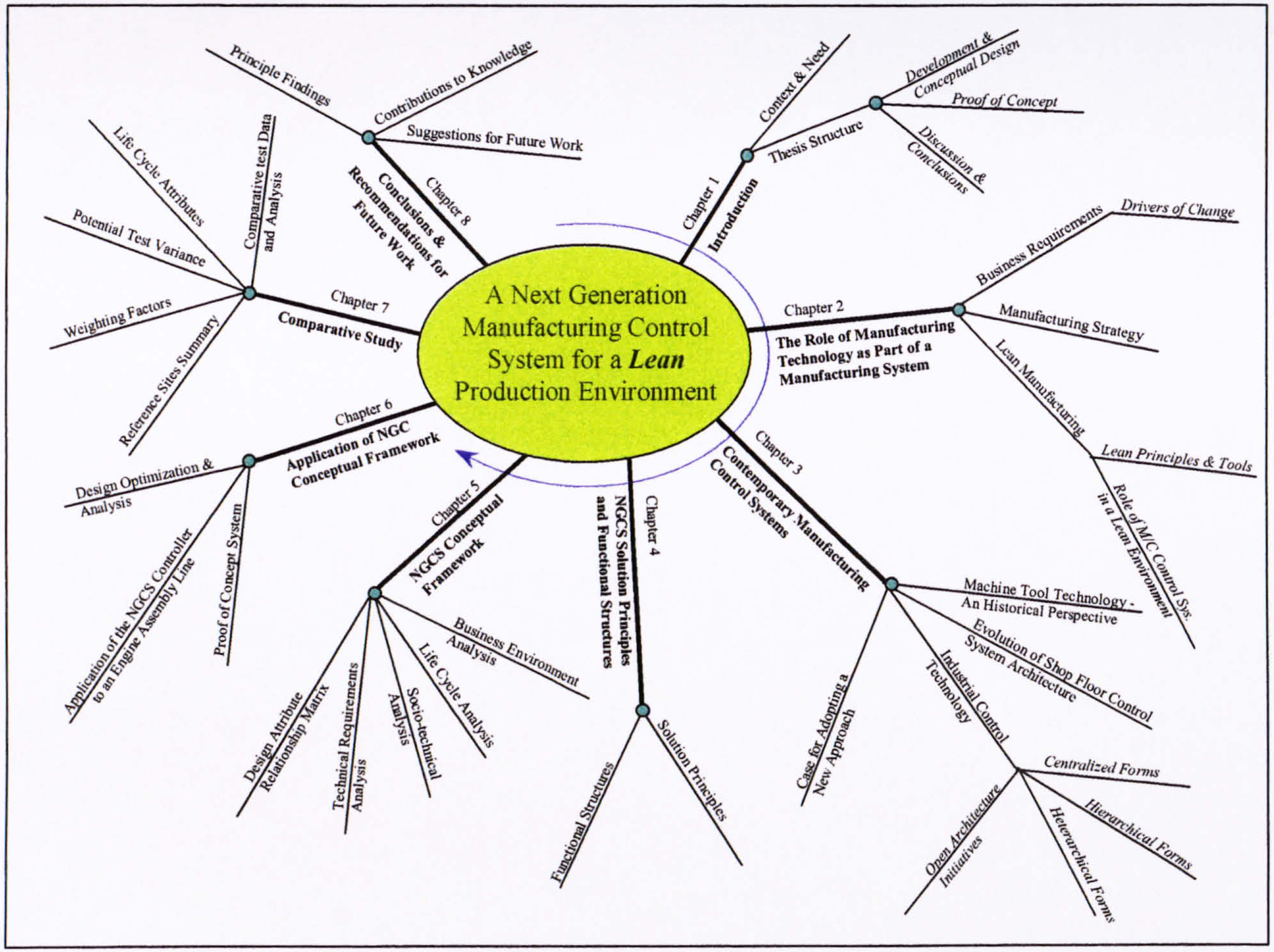
Model

A *model* is considered to be a ***particular instance of a Reference Architecture used to analyse and predict the performance of a system.***

CHAPTER 1

INTRODUCTION

Dissertation Overview



1. Introduction

This thesis focuses on addressing the machine control requirements of the automotive industry and in particular high volume engine manufacture. It will show that whilst the operational domain in the automotive industry has moved to *lean production* techniques (Section 2.2), the design of contemporary manufacturing control systems is inappropriately based on the requirements of a *mass production* environment.

The hypothesis on which this thesis is based is that the design and implementation of present day manufacturing control systems is inappropriate when viewed from a business context. The author proposes that it is possible to create a more appropriate next generation of manufacturing control systems based on the optimised use of advanced manufacturing technology that better meets the needs of a lean manufacturing environment. This thesis therefore aims to provide a contribution to the development of a new design framework that identifies the design attributes required of a next generation manufacturing control system in order to enhance the business performance of *lean* automotive manufacturing facilities.

In order to address this hypothesis the author considers that it is necessary to:

1. Study and characterise contemporary manufacturing paradigms with a view to identifying key strategic issues in automotive manufacturing.
2. Consider manufacturing strategies that are currently adopted within this environment.
3. Identify the role of manufacturing control systems as part of an advanced manufacturing system.
4. Critically review current and emerging manufacturing control technologies and architectures.
5. Consider how manufacturing control technology (MCT) may be aligned and used to best fulfil manufacturing strategy.
6. Identify solution principles and functional structures that will underpin a conceptual design framework that will produce a next generation control system.
7. Create and test a next generation manufacturing control system based on optimised use of available manufacturing control technology within the complete business context.

To clearly define the scope of the thesis a brief overview of the context of the research, the adopted design and development process, the primary attributes of the resultant Next

Generation Control System (NGCS) and the evaluation undertaken is given below in section 1.1. Throughout this section the NGCS approach is contrasted with traditional design and development methods to highlight the research focus of the thesis. The structure of the thesis is detailed in section 1.2.

1.1 Research Focus of the Thesis

The changes in characteristics and aims of manufacturing practices over the last 30 years are illustrated in Figure 1-1. This diagram has been derived from Maskell at al 1998 and summarises typical business environments for four development stages, namely: traditional manufacture, gaining control, world class manufacture and agile manufacture. The aim is to provide the reader with an appreciation of the environment and requirements (i) in which PLC based control was adopted and (ii) that has lead to the NGCS research reported within this thesis. PLC based control of manufacturing systems was developed under the *Traditional Manufacture* and *Gaining Control* paradigms where departmentalism and movements towards better control, planned operations and better communications were adequately addressed (see Chapter 2). The movement towards *lean* and *agile* manufacture requiring less costly systems that are more responsive to change and address long-term profitability, highlights the limitations of present day manufacturing control system development processes. This new operational environment places a much greater emphasis on the system lifecycle and socio-technical issues of designing, implementing, maintaining and reusing control systems within complex manufacturing environments, employing a smaller multi-skilled workforce. The NGCS process addresses requirements to facilitate the achievement of flexibility (with respect to manufacturing structure and customer requirements), organisation (for change and uncertainty) and virtual corporations (to achieve competition through co-operation) that are the cornerstones of an *Agile Manufacture* paradigm.

A comparison of the work described in this thesis (NGCS Process) with the current state of the art (traditional control system development process) is illustrated in Figure 1-2. The differences between the NGCS approach and traditional processes are highlighted in italic for each of the different phases. The Life Cycle phases covering design implementation and system application / operation contain similar generic activities (albeit producing radically different solutions) in the NGCS and PLC processes (see Figure 1-3). In both cases reference architectures are adopted which in turn are utilised to generate practical implementations.

The NGCS Conceptual Framework presented in Chapter 5 is a single integrated design and development method. In contrast the traditional approach involves a number of methods each with a limited scope, focused on a specific system component (e.g. Controller, Power Supply, Drives, Man machine Interface). In the Design Requirements Analysis and Capture phase, the standard practices of Business Environment Analysis (BEA) and Technical Requirements Analysis (TRA) are supplemented in the NGCS process by Life Cycle Analysis (LCA) and Socio-technical Analysis (STA.) (see Chapter 5). The design and development tools used to support the LCA and STA activities are detailed in the same chapter. A key feature of the NGCS process is the capture and analysis of the complete system requirements via the Design Attribute Relationship Matrix (DARM). The DARM enables the mapping of business drivers through all the phases to operational requirements and from there to design attributes.

Feedback (e.g. in terms of cost, quality and time) for the optimisation of the NGCS design is a vital component of the NGCS process developed in this thesis. Under the current state of the art there is no formalised mechanism to enable the lessons learned from particular solutions to be appreciated in future system development. The NGCS addresses this shortfall by ensuring that a Feedback for Design Optimisation activity is undertaken. Details of the optimisation activity and lessons learned are given in Chapter 6.

The outcome of the traditional approach to control system development and the NGCS approach is illustrated in Figure 1-3. In the traditional approach the components (i.e. the Programmable Logic Controller (PLC), input and output (I/O) devices, and drives) are vendor specific and are integrated in an ad-hoc manner. The design approach adopted is fragmented with each of the system components (e.g. RS232 ports, networks, and parallel interfaces) being configured by a different vendor specific design tool. System configuration data (i.e. for the I/O, User Interface and Drives) is held in a number of separate files. Such a system inevitably relies on highly skilled specialists for its commissioning and maintenance.

The NGCS approach utilises an open, integrated system architecture encompassing the complete system (e.g. the controller, I/O, drives, Power Supply Unit). Open standards are utilised to provide vendor independence where possible. An integrated design approach is adopted with a single location for all system configuration data. The system is designed to be commissioned and maintained by multi-skilled operators.

A *Proof of Concept System* is presented in Chapter 6, with a particular focus on attributes that differ from contemporary control systems. The second part of the chapter describes Simultaneous Engineering led by the author with the aim of realising the NGCS design principles on a new high volume assembly line at Ford Motor Company's Dagenham Engine Plant. Evaluation of the NGCS solutions has involved consideration of a number of issues that are illustrated in Figure 1-4. Experimental design has been undertaken to determine both quantitative and qualitative assessment of cost, system abilities and external influences on a lean production system from a number of different perspectives (e.g. operators, supervisors, production managers). Details of the experimental design analysis are given in Chapter 7.

Figure 1-1 Characteristics and Aims of Manufacturing Practices.

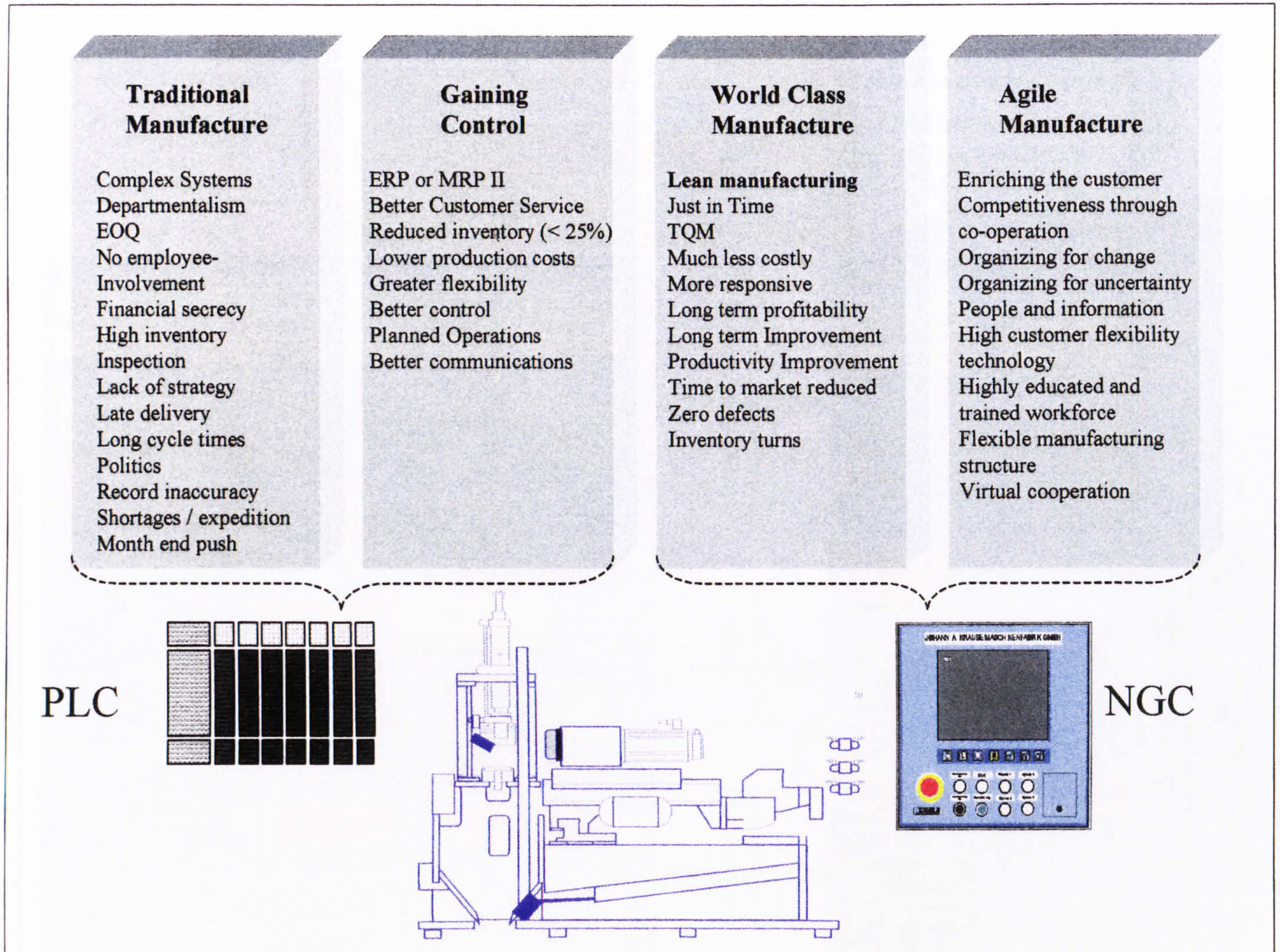


Figure 1-2 Comparison of NGCS Design Process & Traditional Design Approach

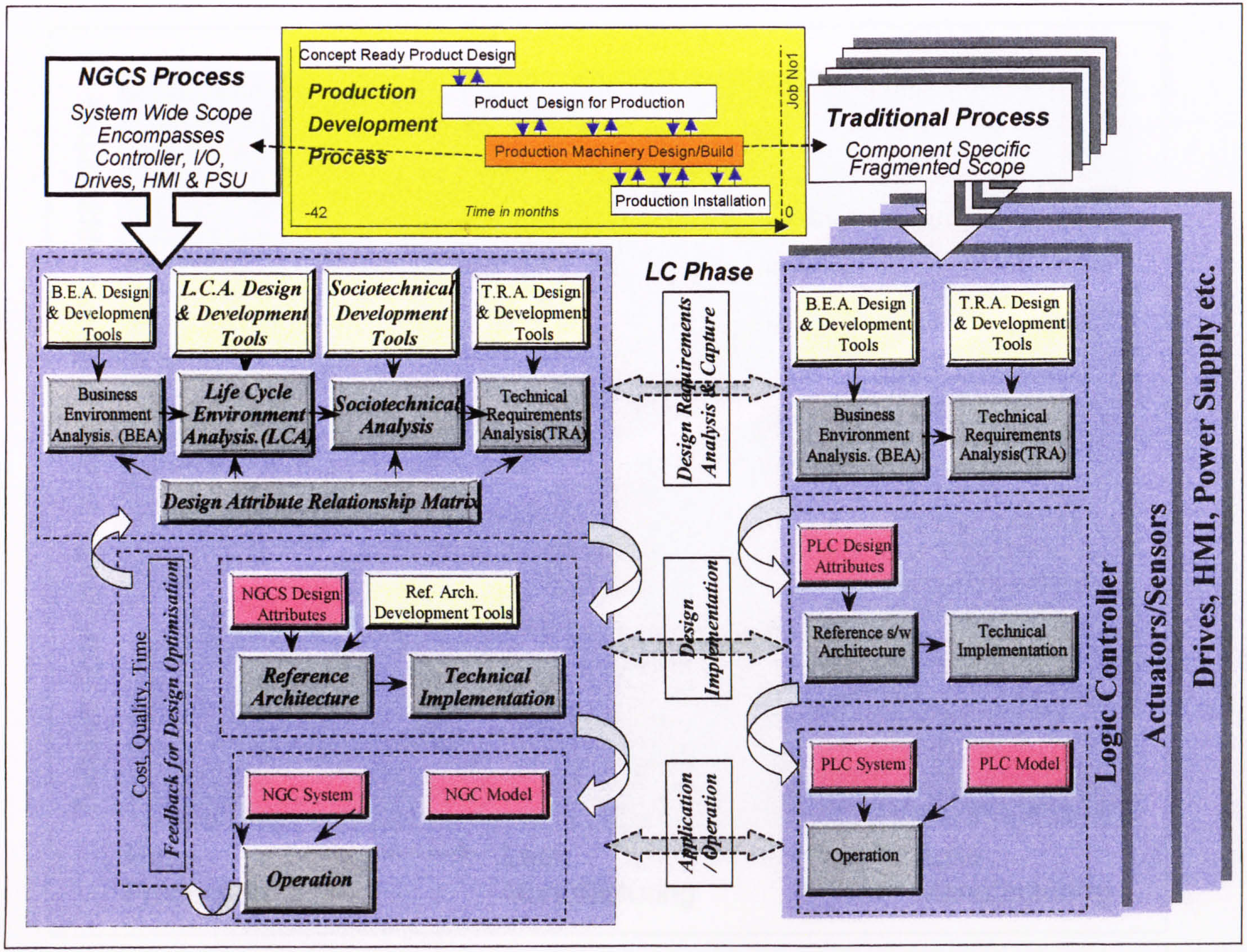


Figure 1-3 Comparison of NGCS and Traditional Control System Attributes

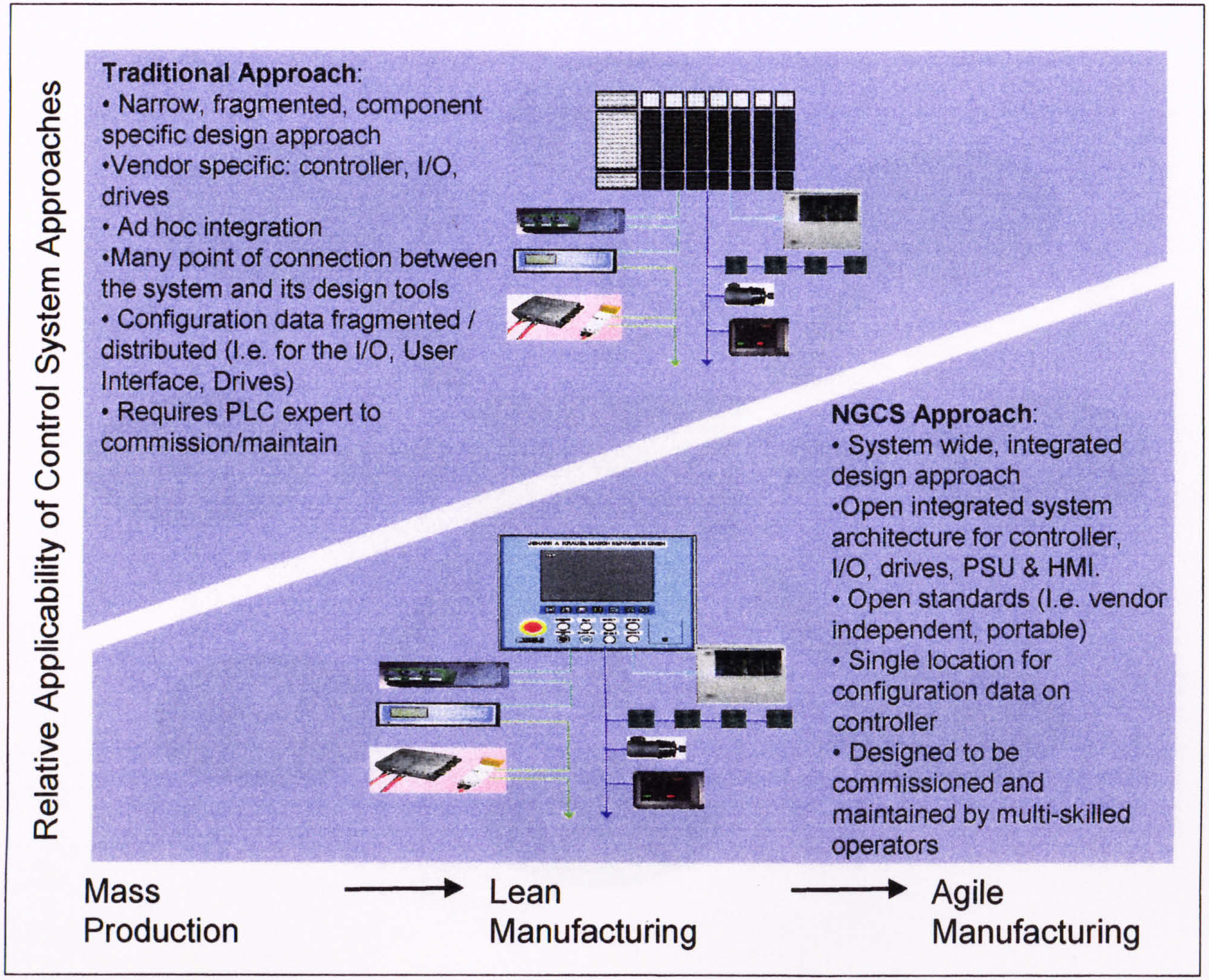
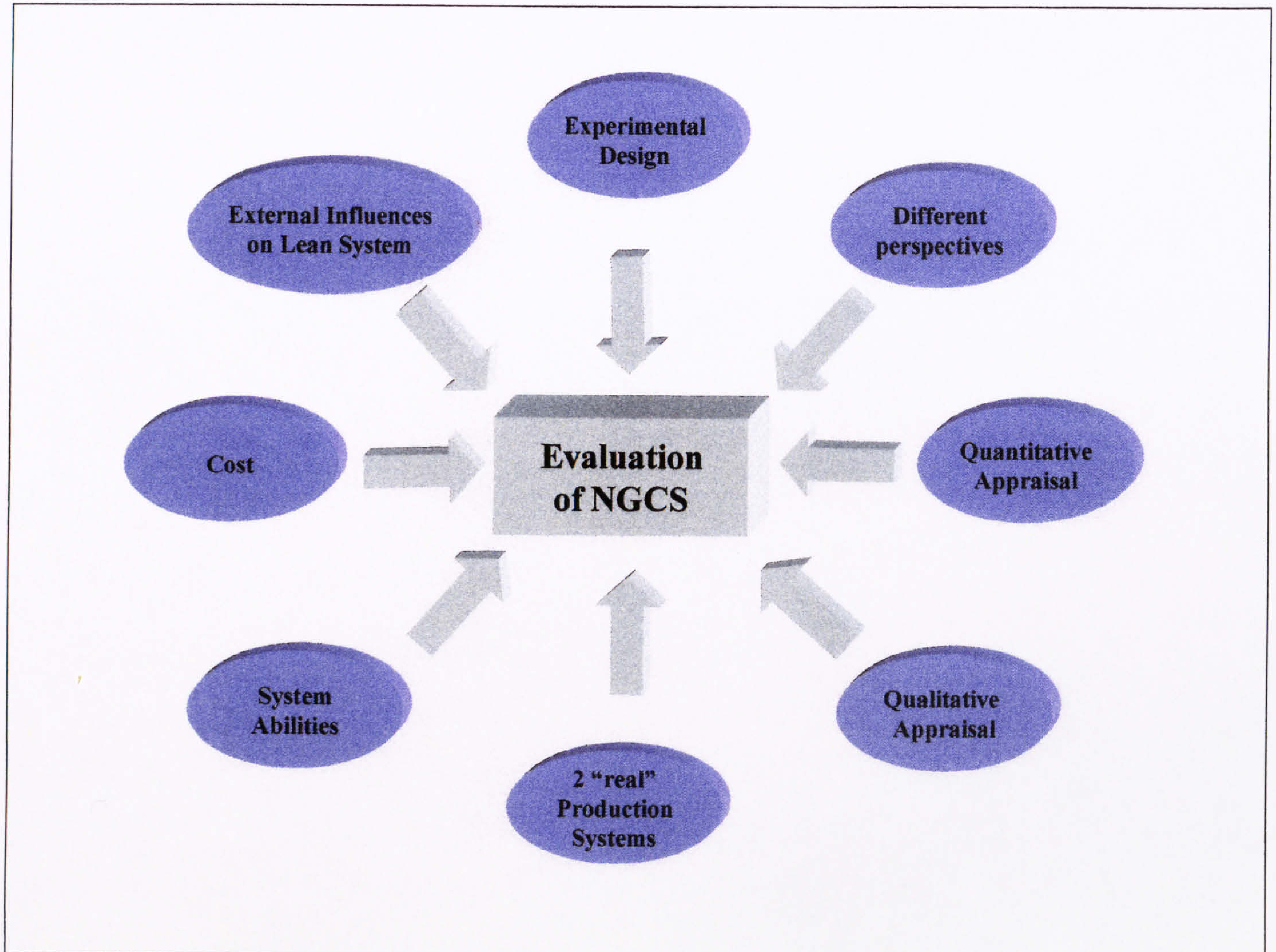


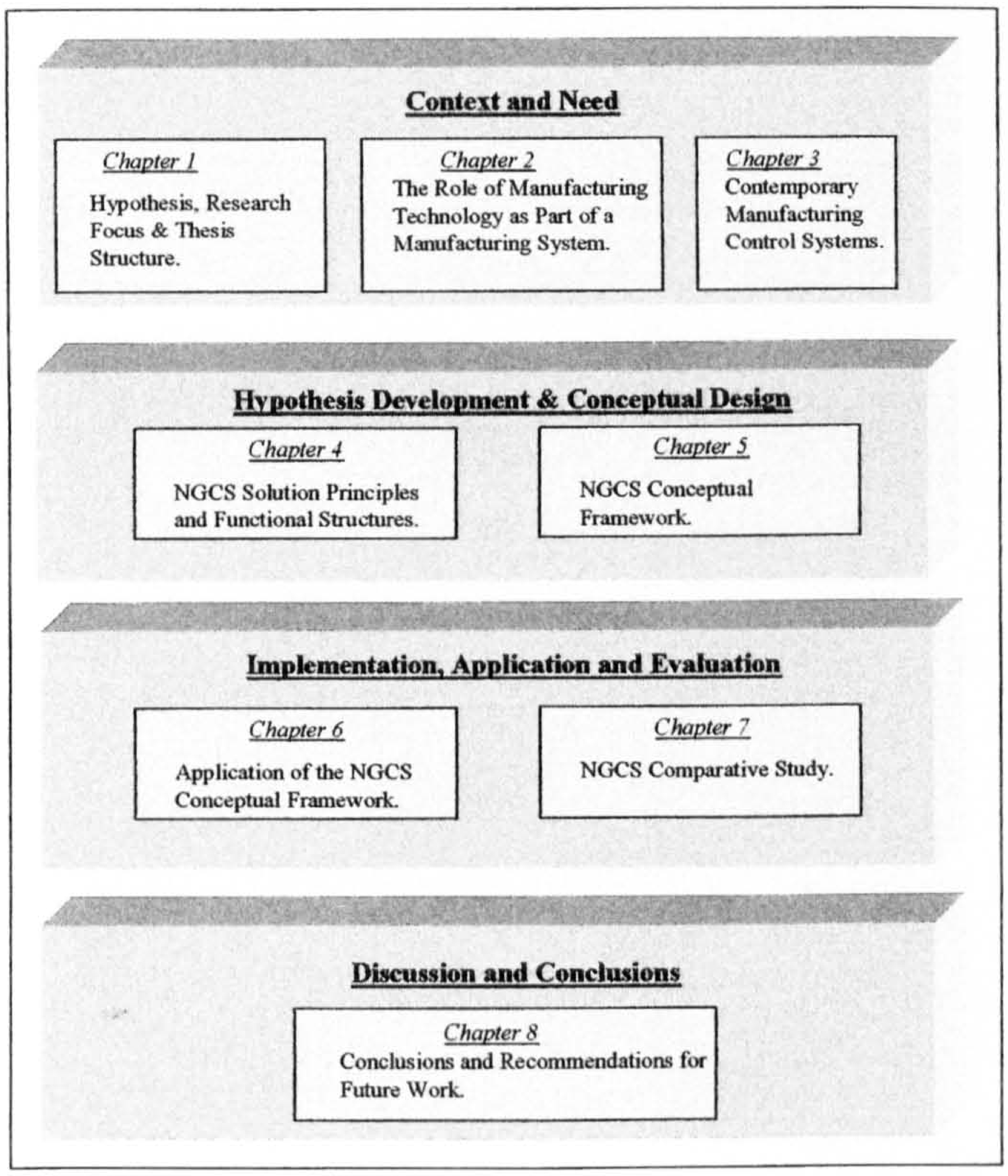
Figure 1-4 NGCS Evaluation Components



1.2 Structure of Thesis

The thesis is broken down into four principle sections, namely: context and need, hypothesis development and conceptual design, implementation and evaluation, and finally discussion and conclusions. The *Thesis Structure* shown in Figure 1-5 demonstrates how each chapter is positioned within this structure.

Figure 1-5 Thesis Structure



1.2.1 Context and Need

Chapter 2 discusses manufacturing control technology within the context of a manufacturing system. A review of the methodology associated with the life cycle cost of manufacturing systems is presented and life cycle costing of manufacturing control systems is considered. Literature is reviewed to provide a detailed understanding of the relationship between modern operating practices and the application of present-day control systems. The primary tasks of manufacturing control systems in the wider context of a structured systems approach to manufacturing technology, production management and industrial economics are identified.

Chapter 3 reviews current manufacturing controls systems, highlighting the fundamental principles that influence application engineering in this area. The literature survey goes on to highlight the limitations of current systems and critiques emerging trends. Attention is paid to the state of the art in manufacturing control systems, by encompassing a review of relevant standards and research initiatives.

1.2.2 Hypothesis Development and Conceptual Design

Chapter 4 draws conclusions from the literature survey and proposes a case for adopting a new approach. A set of guidelines for the development of a next generation manufacturing control system are proposed. The stated hypotheses is developed and examined against the research data. The operations and activities that occur within increasingly complex manufacturing systems are represented as a *model* in order to describe in a formal manner the ideal solution with regard to (i) functional requirement and flow; and (ii) dependencies between activities. Standardised terminology and structures allow the development of a clear set of criteria and requirements to allow the development of a Next Generation Manufacturing Control System (NGCMS) design framework. The design framework identifies contemporary design deficiencies and produces a set of objectives designed to enhance manufacturing performance in a *lean production* environment.

1.2.3 Implementation, Application and Evaluation

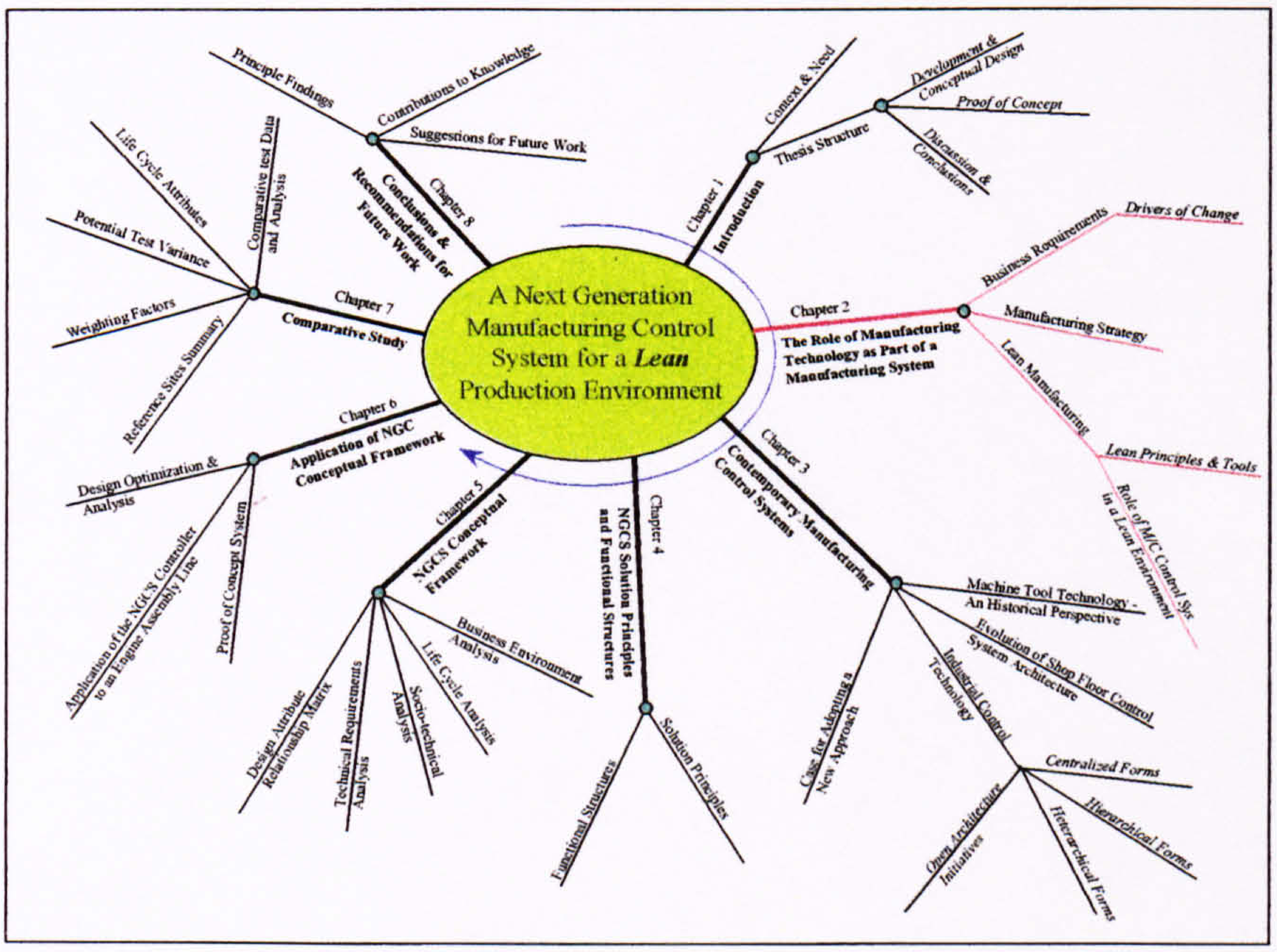
Chapter 6 applies the conceptual design framework to a proof of concept system and shows evidence of applicability. Deviations from the model are discussed and potential advances to contemporary practice identified. The chapter goes on to describe Simultaneous Engineering activity led by the author with the aim of implementing the design at the Ford Motor Company Limited. The functionality of the new system is tested, and then measured against the performance of a conventional control system in Chapter 7.

1.2.4 Discussion and Conclusions

Chapter 8 discusses the benefits and limitations of adopting the new design methodology. Concluding remarks summarise the principal elements of the work carried out in the thesis. Major contributions to knowledge are listed, highlighting areas where these contributions have satisfied the criteria identified in the body of the work. Finally recommendations for further research are outlined.

CHAPTER 2

THE ROLE OF MANUFACTURING CONTROL TECHNOLOGY AS PART OF A MANUFACTURING SYSTEM



2. The Role of Manufacturing Control Technology as part of a Manufacturing System

2.1 Introduction

The aim of this chapter is to consider the role of automation and in particular machine control systems within the context of modern manufacturing strategy. The chapter is divided into two sections. The first section considers present-day business requirements and drivers of change. Manufacturing strategies employed to fulfil these requirements are considered. The second part of the chapter identifies the role that manufacturing control systems have in supporting current manufacturing strategy.

2.2 Business Requirements and Drivers of Change in the Automotive Industry

The business environment now faced by manufacturing companies is significantly more competitive and dynamic than anything experienced in the past. Some of the trends that characterise this include: [Fuchs 1996] [Furness 1996] [Rao 1993] [Shaharoun 1993] [Singh 1996] [Wobbe 1994].

- globalisation of technology and markets;
- fragmented, sophisticated, and demanding customers;
- complex products with fused technologies;
- rapid product and process technology changes;
- environmentally conscious manufacturing.

During the life of the automotive industry, expanding markets and global competition led to Taylorist and Fordist principles of work organisation. Managers viewed specialisation and high levels of automation as key enablers in achieving these principles. The shift to customised quality products has grown at the cost of standardised *mass production* leading to an increase in product variants and quality features, and a decrease in batch sizes and product life. These changes have had a dramatic impact on company management and organisation. Traditional automotive producers based on mass product and price competition are losing out to *lean* producers mainly from the Far East who offer greater flexibility, lower overall cost and higher quality.

Slow or nil growth in many developed economies is enticing the automotive companies into developing markets such as India, China, and South America. Pressure is being placed upon manufacturers to compete not just on cost, but on quality, flexibility, and innovation. Skinner promotes the view that successful companies must learn to use their manufacturing effectiveness as a competitive weapon, [Skinner 1985].

Over the last thirty years Managers have often looked on electrical, electronic and programmable systems as one of the key enablers in realising initially the goal of *mass production* and more recently *lean production* principles. In the 1980s many Western manufacturers installed thousands of the latest Robots, CNCs and Programmable systems in an unsuccessful attempt to match Japanese productivity, flexibility and quality. There is clear evidence that the Japanese consistently used relatively simple control equipment, concentrating instead on using appropriate levels of technology that allowed them to improve flexibility. The same basic manufacturing control technology was available globally implying that the Japanese utilised available technology more effectively in their manufacturing systems. Western *mass production* companies clearly failed as can be seen from the almost universal adoption of lower levels of automation and Japanese *lean production* techniques.

Despite the ubiquitous acceptance of *lean production*, considerable uncertainty still exists both in Japan and the West concerning the introduction of automation. Deficiencies in current automation systems is often concealed through the use of highly skilled shopfloor staff and costly engineering to initially configure, maintain and then reconfigure the systems. Manufacturing Technology is often viewed from a narrow technical view point, ignoring the broader strategic awareness. Successful manufacturing enterprises require a clear and detailed understanding of the key drivers of change, the strategies required to meet those challenges and finally the advanced methods and technologies that will deliver the desired competitive advantage.

2.3 Manufacturing Strategy.

The vast network of individuals that make up an organisation must be harnessed and directed toward a common set of goals. Garvin, Nutt and Goodman promote the view that the long term success of an enterprise requires a sound strategy, [Garvin 1992], [Nutt 1979], [Goodman 1982]. A corporate strategy implies a consistency in a company's preferences for certain management options including: dominant orientation, pattern of diversification, attitude toward growth and choice of competitive priorities. These strategic preferences are shown in Figure 2-1

Figure 2-1 Corporate Attitudes That Imply Strategic Preferences [Garvin 1992a]

Dominant orientation Market Product or material Technology	
Pattern of diversification Product Market (geographic or consumer group) Process (vertical integration) Unrelated horizontal (conglomerate)	
Corporate attitude to growth Growth sought explicitly Growth viewed as a by-product of successful management of the 'core' business.	
Competitive priorities Dependability Product flexibility Price	 Quality Volume flexibility

The concept of a manufacturing strategy is a natural extension of this concept. Manufacturing must arrange its structure, management and production technology to facilitate the support of the corporate strategy.

The lack of a manufacturing strategy or failure to communicate the strategy to the team tasked with implementing the control system, often leads to supplier and technology selection carried out on a short term economic basis rather than as a result of a long-term business need. The impact of poor interaction and integration of suppliers into the project team is felt more in the automotive sector than any other [DTI 1995]. A recent report published by the Department of Trade and Industry compares developments between suppliers and car manufacturers in the UK, Japan and the USA. The report concludes that in the UK partnerships have progressively improved over the past few years with:

- sixty four percent of suppliers surveyed reporting that they are developing partnerships with vehicle manufacturers,

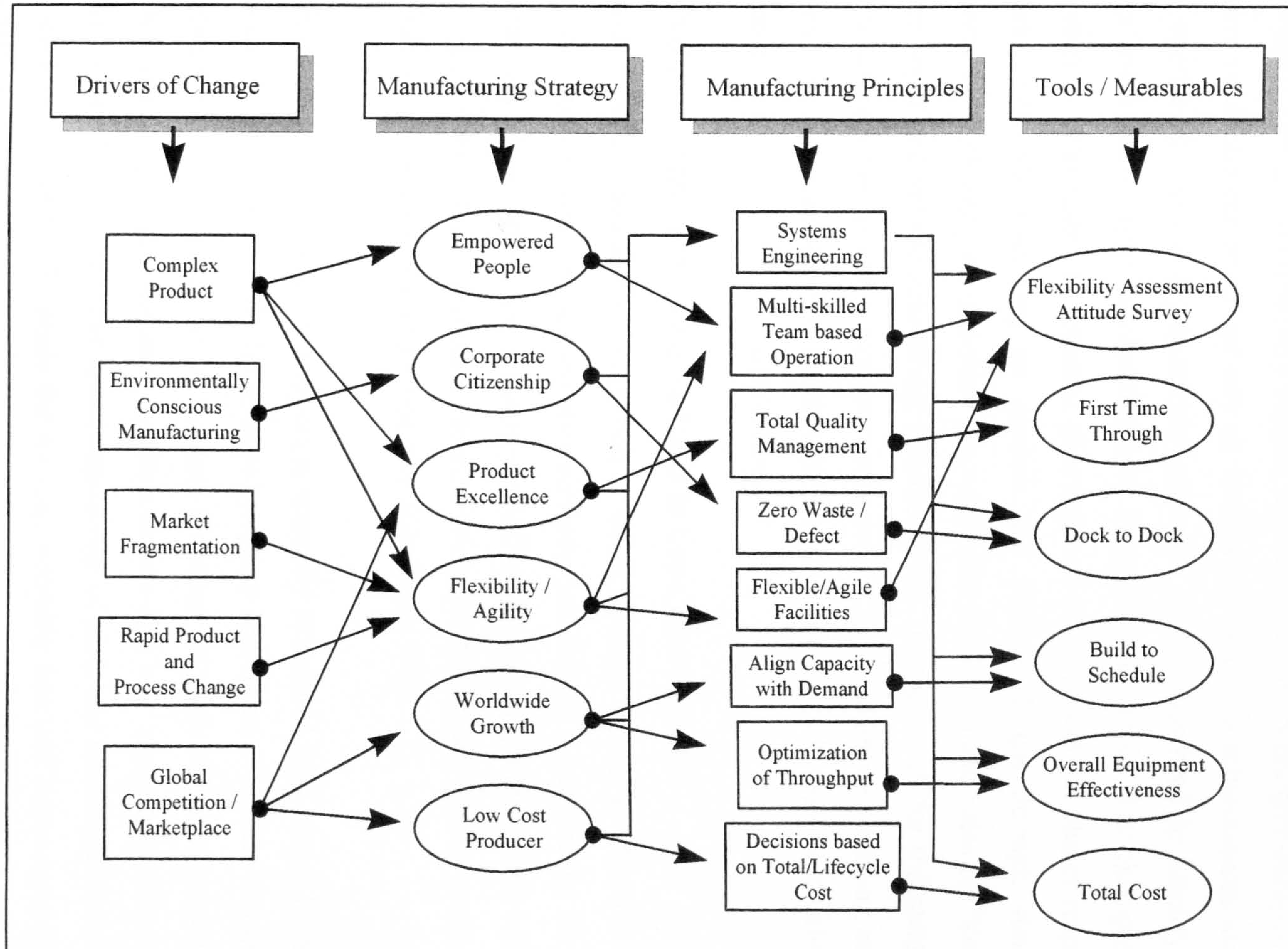
- the proportion of UK suppliers who believe that their customer would help them improve performance in the face of competition increasing from 39% in 1989 to 81% in 1995 and,
- UK suppliers matching their Japanese counterparts in demonstrating the greatest confidence in their customers' commitment to maintaining the relationship.

In contrast Pollack reports that in Japan the supplier, end user base is breaking down as automotive suppliers look to overseas suppliers who are able to offer more cost effective contracts and are breaking away from long-term partnerships with their *local* supplier base [Pollack 1995].

Hakensson and Ostberg present a model that considers the relationship between suppliers and users as the major dependent variable, [Hakansson 1975]. The model explains situational aspects which lead suppliers and developers to innovate and users' willingness to adopt the developed innovations and technologies. The model suggests that the level of co-operation is based on a *social exchange process* and a degree of fit in the adaptation of the technology both from economic and technological grounds. However in the development of AMT systems the Hakensson and Ostberg model assumes that organisational changes in the production system are carried out after the decision to accommodate the innovation is made [Zairi 1998a]. It can be deduced from this that manufacturing strategy has not been incorporated in the model.

Increasing research attention is being given to production competence as the source of competitive advantage [Choe 1997], [Cleveland 1989]. Cleveland *et al* define production competence as 'the function of the fit between business strategy contents and manufacturing strategy contents'. They report empirical evidence supporting a significant relationship between production performance and business performance.

Figure 2-2 Advanced Manufacturing Strategies for High Volume Automotive Manufacture.



2.4 Lean Manufacturing Principles

2.4.1 Introduction

A review of the manufacturing strategies employed by automotive manufacturers reveal a broadly common set of goals as summarised in Figure 2-2, [FMC 1998], [VW 1998], [Daimler-Benz 1997]. To effectively support the manufacturing strategies outlined the large automotive producers can no longer rely on functional or regional achievements instead they need to operate as a single organisational structure. Companies need to identify how the processes within these organisational functions integrate and overlap. For example, Product Development is responsible for product planning and development. It shares responsibility and works with Manufacturing on product and process design through simultaneous engineering and both integrate and share processes with Marketing and Sales for 'Voice of the Customer' input and vehicle scheduling, [Sapota 1998]. In the search for the most efficient method to address this dynamic environment a review of contemporary leading automotive producer's manufacturing strategy reveals that in every case Toyota's *Lean* Production System model has been used as a source of inspiration.

2.4.2 Evolution of Manufacturing Methods to Lean Manufacture

Lean production is aimed at the elimination of waste in every area of production including: customer relations, product design, supplier networks and factory management. Its goal is to incorporate less human effort, less inventory, less time to develop products, and less space to become highly responsive to customer demand while producing top quality products in the most efficient and economical manner possible, [Cochran 1998].

The birth of the modern manufacturing era is normally associated with Henry Ford's Model T. With this vehicle Ford had finally achieved two key objectives. The first was that almost anyone could drive and repair the car without the need for a chauffeur or mechanic. The second and more important innovation was that the product was *'designed for manufacture'*. It was this complete and consistent interchangeability of parts and the simplicity of attaching them to each other that finally made the moving assembly line and hence *mass production* possible [Womack 1990].

The idea of interchangeability of parts was first developed by General Jean-Baptiste de Gribeauval in the second half of the eighteenth century [Batchelor 1994]. His incentive was the efficient maintenance and repair of guns. This system, which reduced reliance on skilled craftsmen, attracted the attention of the United States Ordnance Department. Under the Ordnance Department's patronage interchangeability was promoted in both its own and private armouries, [Rolt 1986].

The second key enabler of m*ass production* involved breaking complex tasks into a series of simple operations with a set target time for each [Liepietz]. In the late 19th century Taylor of the Bethlehem Steel Company published a new philosophy for manufacturing management that put forward such a principle including the payment of bonuses to those that achieved them. Ford adopted Taylor's principles.

Henry Ford's *mass production* drove the auto industry for more than half a century and was eventually adopted in almost every field of industrial activity in North America and Europe [Womack 1990a].

Henry Ford recognised the importance of eliminating waste within the manufacturing environment and designed the Ford industrial structure accordingly [Ford 1926]. After World War II, the manufacturing capacity of U.S. companies dominated the world market place with domestic manufacturers having little competition. Such conditions encouraged wasteful practices and allowed unsound managerial polices to evolve. The focus of many organisations shifted to meet market demand at any cost.

The managers of *mass production* factories forgot some of the lessons that Ford had laid down and in an attempt to meet market demand unwittingly shifted their focus away from synchronised production flow to the attributes summarised below:

- high levels of indirect labour including relief workers, trouble shooters and housekeepers,
- high levels of in process stock used to buffer the production operation from uncontrolled events; for example, breakdowns, stock shortages,
- extensive end of line test and repair facilities,
- high volume dedicated production facilities.

Mass production had evolved into a system that attempted to isolate the factory operations from its own deficiencies and outside disturbances. In contrast in Japan a system started to evolve that deliberately exposed the manufacturing facility to the market. This new approach is commonly known as *lean production.*

A five year study by the Massachusetts Institute of Technology on the automotive industry reported a number of problems witnessed in *mass production* facilities including: poorly balanced production lines, assembly process problems with no root cause procedure, a dispirited workforce, no career progression for production workers and engineers progressing through their area of technical expertise with little experience of production.

In 1950 a young Japanese engineer, Eiji Toyoda spent several months studying Ford Motor Company's Rouge Plant in Detroit. Back home in Nagoya, he came to the conclusion that the *mass production* techniques he had witnessed could never work in Japan [Womack1990b]. The reasons for this conclusion were: the market for Japanese vehicles was much smaller, therefore high volume single product manufacturing facilities were unsuited, the native Japanese work force was not made up of temporary 'guest' workers willing to put up with sub-standard work conditions; (In the West by contrast, these individuals had formed the core of the work force.); and finally, the war-ravaged Japanese economy was starved of capital, meaning that purchase of the latest Western production technology was out of the question.

The key attributes of *lean production* can be summarised as follows:

- complete and consistent interchangeability of parts and the simplicity of attaching them to each other with a root cause identification procedure for any part that fails to assemble correctly,
- breaking complex tasks into a series of simple operations with a set target time for each [Liepietz],
- low levels of indirect labour. The majority of repairs and housekeeping is carried out by the production team,
- low levels of in process stock,
- very little end of line test and repair,
- compact layouts facilitating face to face contact and leaving no room to store inventories,
- high levels of empowerment to the team workers adding value to the vehicle,
- multi-skilled workforce,
- continuous improvement on a proactive basis at all levels,
- every employee begins by working on the production line for some period of time,
- more flexible (than *mass production*) production facilities.

2.5 Lean Manufacturing Tools and Measurables

Manufacturing tools to assist in the delivery of *lean* manufacturing strategies are shown in Figure 2-2. These techniques represent the primary means of producing an efficient manufacturing system, [Tang 1997], [Paashuis 1997], [Womack 1990b].

2.5.1 Systems Engineering

Modern society functions within the framework of a physical infrastructure which is vast, complex and pervasive [Dandy 1989]. Manufacturing (the production of tangible goods or products) has a history extending back several thousand years, [Hitomi 1996]. In 1991 the National Academy of Engineering and Science in Washington, D.C. rated 'manufacturing' as one of three most important subjects necessary for America's economic growth and national security, the others being 'science' and 'technology'.

Today, manufacturing must considered not only from the technological view but also from wider standpoints such as management, economy, social sciences and philosophy. The study of manufacturing and production must include both hard and soft technologies. Such an integrated study of manufacturing is termed 'manufacturing systems engineering', [Hitomo 1996a]. Systems theory emerged as a field of study from the biological and engineering sciences, [Aguiar 1995]. The application of systems theory to organisations emanates from cybernetics[2] in particular the works of Beer, (viable system model), Forester, (system dynamics), Stacey, (strategic management and organisational dynamics) and Ashby (an introduction to cybernetics), [Espejo 1996].

Stacey states that: 'organisations are open systems comprised of interconnected parts which interact with one another and with their environment.' The system imports energy and information from its environment and exports the transformed results. Imports and exports occur across the organisations boundary.

Work in contemporary global organisations is co-operative, often involving vast networks of individuals. Espejo *et al* [Espejo 1996a] reason that managers often lack the means to measure the complexity of organisational tasks and therefore rely on their 'intuition or good luck' for successful decision making. Designers of modern advanced manufacturing systems must take account of these factors to ensure that the one sided interest of engineers in

[2] Cybernetics - taken to be: 'science of effective organization'

technical aspects, does not result in the neglect of social and organisational issues and therefore lead to the creation and implementation of inadequately functioning systems.

In his inaugural address the current President of the IEE stated; 'Education in the methods, tools and techniques of systems engineering will be essential for all engineers for the future.' Real world-class competitiveness comes only from the successful combination of two elements: [Parnaby 1995]

- soft system methodologies - procedural tools, heuristic techniques and new organisational practices,
- hard technologies - for developing products, production processes and utilising modern capital equipment.

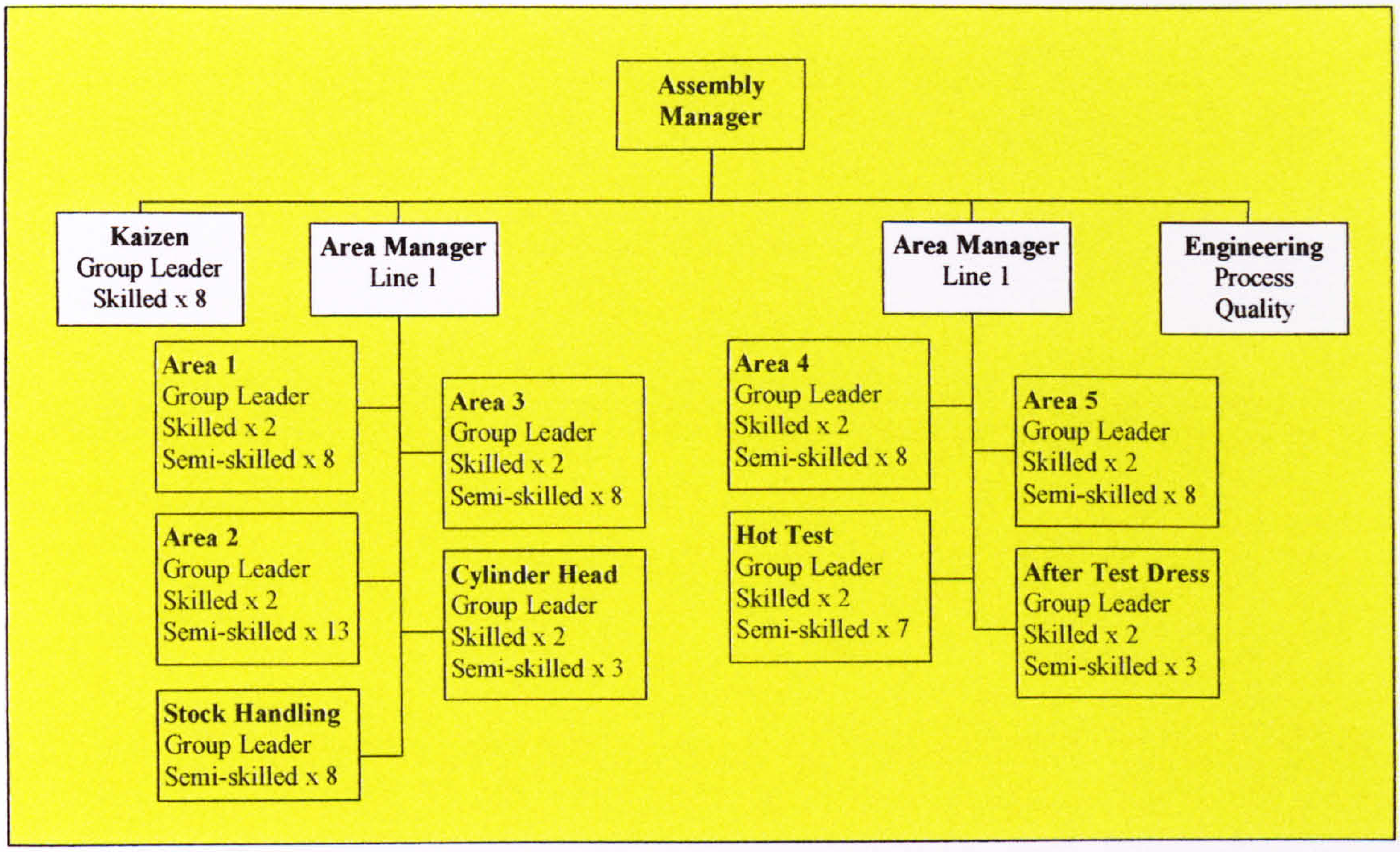
2.5.2 Multi-Skilled Work Groups

The latest technology, equipment or material is no substitute for the ability and creativity of satisfied people, successfully and safely working together. Participating within a multi-skilled group provides the benefits of a broad knowledge base and diverse experiences to better analyse problems and reach solutions. Effective work groups are built around capable, motivated and empowered people who trust and rely on each other, [Sopata 98].

The keys to making this principle work are education, training, communication and appropriate technology. The work group is most effective when it has the full picture of what and why a task needs to be accomplished.. Objectives can then be aligned and work together to meet them and take ownership in the process and the results.

The structure of an example assembly workgroup is shown in Figure 2-3. The groups are a mixture of skilled and semi-skilled operators working within a flexible environment. This provides greater job satisfaction than the traditional *mass production* models that limited operators to a single operation. The skills mix within the team raises the skill level of operators and supports lower mean time to repair due to the quicker response time. Peak workloads can be shared, due to each individual's greater knowledge of the overall process and increased flexibility, allowing higher overall loading and productivity.

Figure 2-3 Assembly Workgroup Structure



Ford sets the objective for an effective work group by setting targets against the team's success rate, (ability to achieve the task) a job satisfaction measure and finally a measure based on safety. Progress is tracked by monitoring:

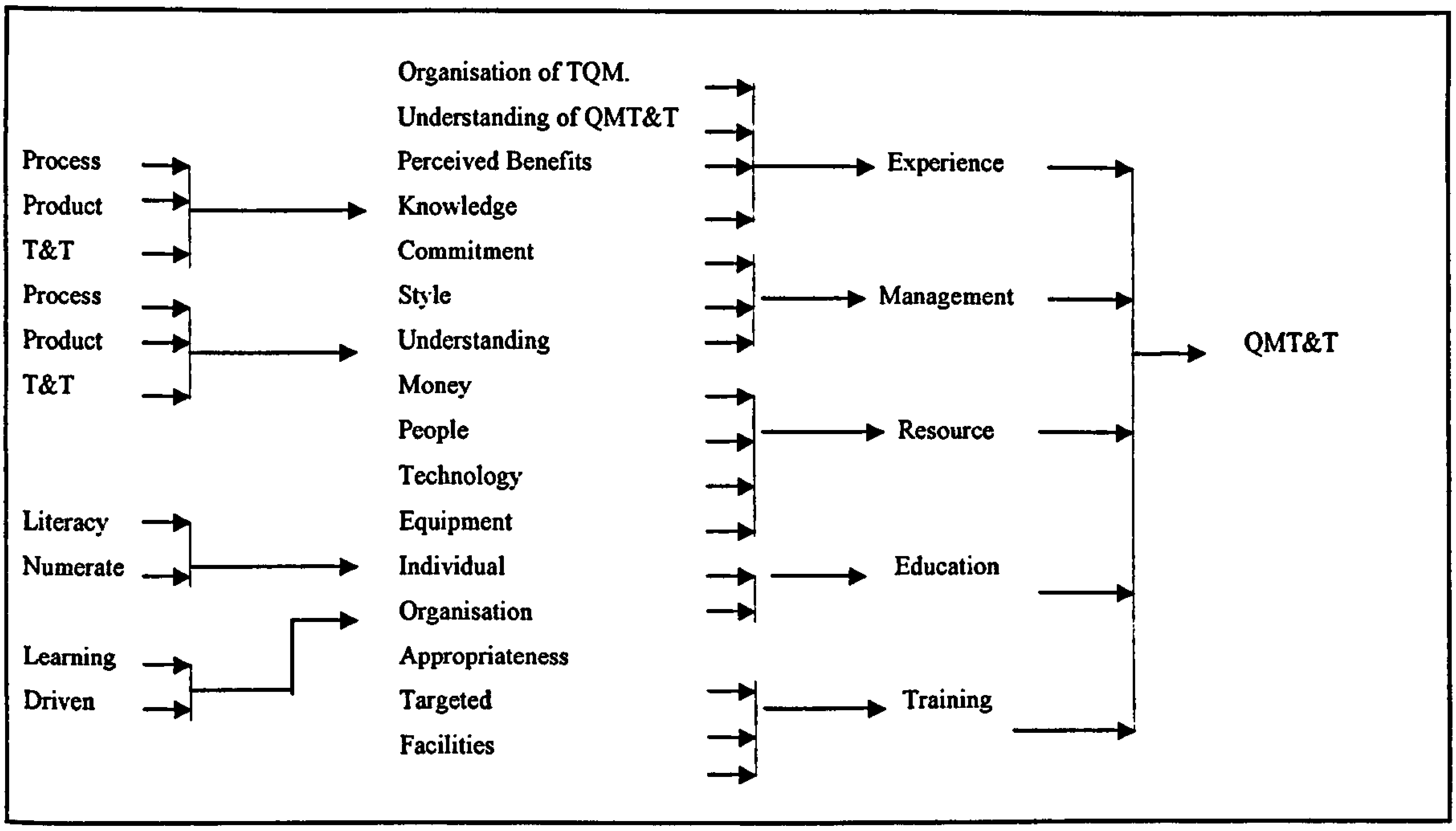
- how consistently the group demonstrates continuous improvement in meeting the aligned objectives of the group and the Company,
- surveys of our attitudes about our job and working environment,
- a Safety and Health Assessment Review Process.

2.5.3 Total Quality Management

Quality excellence is best achieved by preventing problems rather than by detecting and correcting them after they occur. All functions carried out by the manufacturing system is part of a process that creates a product or service for a customer. Each person can influence some part of that process and, therefore, affect the quality of its output and the ultimate customers' satisfaction, [Peterson 1985].

The variety of techniques and by their very nature their complexity often leads to difficulties in their selection, application and use. Empirical evidence collected by McQuarter [McQuater 1994] shows that five factors have an effect on Quality Management Techniques. They are: experience, management, resourcing, education and training. McQuarter *et al* claim that "it is the accumulation of these influences that yield a cascade effect on quality management tools and techniques (QMT&T) as shown in Figure 2-4.

Figure 2-4 The Cascade Effect of Specific Influences on Quality Management Tools & Techniques.



The Japanese are considered to be the leaders in techniques for the management of quality in manufacturing. Despite this lead the work of two Americans J.M. Juan and W.E. Demming are often cited by the Japanese as highly influential, [Lillrank 1989], [Schonberger 1982].

Kaizen is the Japanese term for improvement. Imai describes *kaizen* as the single most important Japanese management concept, [Imai 1986]. He defines the technique with four characteristics:

1. Improvement combines both innovation and maintenance. Innovation seeks new methods, processes or products; and maintenance ensures that incorporated innovations remain as they should be and do not deteriorate.
2. Improvement normally happens in small steps, through continuous corrections to details.
3. Improvement must involve everyone in the organisation from senior management to shop floor workers.
4. Improvement emphasises the production processes. It is assumed that if the process is good, good results will flow automatically.

From the literature surveyed the author concludes that from a *lean* Manufacturing perspective these factors represent the most significant elements within the five pillars of Total Quality Management (TQM) [Goh 1994].

2.5.4 Zero Waste/Defect

This principle represents continuous efforts to eliminate anything that does not add value to the end product or service. This means eliminating waste of materials, space, equipment, time, energy or indeed the ideas of the organisations people. For example, co-ordinating Supply and Manufacturing processes so that materials flow through the system just as they are needed eliminates the waste of space for storing or purchasing excess inventories.

The principle of Zero Waste/Defect also contributes to improved quality by allowing the immediate feedback to suppliers of issues and minimises the potential of defects being passed to the next phase of the production process. Typically the measures and objectives for this principle are: zero defects made, zero defects passed on and total 'Dock-to-Dock' time.

'Zero defects made and zero defects passed on' is measured by 'first time through capability'. This means that each part or product can progress through every step in the process with the highest quality and without needing repairs or rework. This measurable combines with the 'dock to dock' time to focus attention on the capability of processes.

An important element in achieving 'first time through capability' is understanding the difference between a defect and the root cause error that caused the defect. The elimination of root cause factors is possible if the work group is supported by a system that is based on preventing errors. Examples include: product and process compatibility, robust designs, in-station process control, appropriate technology and an environment that allows a job to be accomplished correctly the first time. All these factors affect whether defects are produced and passed on to the next operation and customer.

The measure of 'Total Dock-to-Dock Time' is defined as the time required to produce a product, for example, from the time material arrives in receiving until the product leaves the plant. This measurable drives the enterprise to consider the integration of people, equipment and material to continuously improve efficiency and speed to market. The manufacturing

Actions designed to improve 'Total Dock-to-Dock Time' and the eliminate non-value-added steps include:

- Concentrating on reducing complexity,
- Improving the reliability of our machines, products and processes,
- Assuring our products are easy to build,
- Continuously improving the efficiency of facilities and work elements.

2.5.5 Flexible/Agile Facilities

The fundamental driver for agile[3] production facilities is change in markets and customer requirements and the alignment of capacity with demand. Market fragmentation into many segments and niches, each with its own set of specific, complex, and rapidly changing needs make agile facilities essential to remain competitive.

The words agile and flexible are often used with little distinction between the two. Despite considerable research literature recognising the crucial importance of flexibility Cheng *et al* show evidence of confusion among the numerous definitions of flexibility and agility, [Cheng 1997].

Gould and Owen agree that the 'agility' of an enterprise is its ability to survive and indeed prosper in an environment of rapid and unpredictable change [Gould 1997], [Owen 1997]. As a subset of an enterprise this definition can equally apply to manufacturing facilities and technology. In contrast *flexibility*[4] as used in the automotive industry is described by Tempelmeier *et al* as a system that can process a limited spectrum of different workpieces in an arbitrary order, [Tempelmeier 1993]. From this it could be said that a flexible system prospers in an environment of planned change.

Gould and Dove discriminate between 'agile' and *lean*' enterprises by describing an agile system as the next step on from the *lean*' concept, (Figure 2-5). Dove highlights the reconfigurability aspect as the main addition to *lean* manufacturing.

[3] Within the context of this Thesis 'Flexible manufacturing' is considered to be a facility designed to rapidly adapt to known product variance. (i.e. 2.0L and 1.8L models). An agile facility is by nature flexible but can in addition can rapidly adapt to unforeseen change. (i.e. the introduction of a new material or product feature).

[4] Flexible facilities in the automotive industry normally consist of several flexible machines with a central transfer mechanism. See [Tempelmeier 1993] P.6.

Figure 2-5 The Evolution to Agility

	Craft	Mass	*Lean*	Agile
Reconfigurable				X
Flexible			X	
Fixed		X		
Comprehensive	X			

Design modularity is an important contributory factor to both flexible and agile systems. The importance of modularity as a feature of design is not limited to production facilities, [Budgen 1995]. In the context of engineering product design, Stoll states that modular construction permits 'standardised diversity' by using different combinations of standard components, [Stoll 1996].

2.5.6 Aligning Capacity with Demand

The ideal situation would be to exactly match each customer's requirements and to deliver these vehicles without delay. Within the constraints of a high volume system, the goal is to get as close to this ideal as possible. To achieve this aim the organisation must work to identify processes that:

- accurately identifies the current and projected needs and wants for all markets,
- makes full use of available capacity to schedule and build vehicles and components to satisfy the immediate demand,
- reduces the time it takes to design, engineer, order, manufacture and deliver vehicles and vehicle sub-systems,
- provide flexible/agile facilities and equipment.

The business objectives are: to build a high percentage of products to market demand, improve the time from order-to-delivery and to optimise capacity and commodity planning. The facilities must support the overall aim by facilitating quick model changeover and allow the introduction of new design features with minimal expense. This principle demands that each element of the production system be disciplined and promotes a sense of urgency in solving problems.

2.5.7 Optimization of Throughput

To survive in the global market place automotive companies must strive to be employ the most efficient facilities, materials and equipment. Organisations must find ways to continuously work better and smarter and make the best use of investments.

Ford identify several enablers that together will allow them to maximise both quality and production volume from existing facilities. Their primary objective is to gain a significant increase in capacity from existing sites with little or no additional investment. The identified enablers are: [Sopota 1998]

- designing product robustness and process compatibility,
- effective capacity planning,
- replicating and using best practices world-wide,
- delivering and maintaining equipment and facilities with world class reliability,
- increasing Overall Equipment Effectiveness (OEE).

OEE looks at the amount of time a piece of equipment is in use and how efficiently it performs to build quality products, [Pierson 1998]. OEE measures performance in areas ('constraints' or 'bottlenecks') that prevent products from flowing at desired levels. Improvements focus on minimising or eliminating bottlenecks in Production, Maintenance and Product changeovers and therefore reinforcing the importance of consistently maintaining the reliability and efficiency of equipment, improving capacity planning, designing for manufacturing and reducing complexity in products and processes.

2.5.8 Total/Life Cycle Cost

In any process or function, looking at the costs of labour, equipment, quality, shipping, inventory, material and other elements as parts of a total system, provides the data required to make knowledgeable trade-offs to achieve the best overall results, [Sheng 1997].

The period from conception, through to design, production, marketing and product change has shrunk rapidly in recent years as companies try to reduce time-to-market. Cost recovery of investment and shareholder value have become major topics of discussion generating issues of concern for the manufacturing facility designer, [Kirk 1995], [Kolli 1992], [Lavelle 1992], [Boelzing 1989] [Nassau 1998]. Issues include facility obsolescence and reuse, environmental sustainability, operational effectiveness (re-engineering), total quality management (TQM) and value engineering (VE) [Kirk 1995a]. These factors have led to the various stages of the automation's life-cycle to be carefully examined in the search for cost improvement and competitive advantage.

Life Cycle Cost (LCC) is the total cost of ownership of a piece of equipment during its operational life. The cost of support over the life-cycle is usually much more than the initial acquisition cost. Acquisition cost is primarily concerned with the conceptual design, build, and installation phases of the equipment life cycle and is a non-recurring cost, while the support cost goes on until the system is decommissioned. This does not allow these phases to be ignored. Hagen and Whitney estimate that 80 to 95% of the support costs are determined during the concept and design phases, [Hagen 1997], [Whitney 1988].

By looking beyond initial investment cost, long term gains can be achieved. A key enabler of this process is a thorough understanding of the business; how it has worked in the past, what the current needs are, and finally the likely requirements in five or ten years.

Life-cycle economic profiles are typically based on a standard life-cycle model. A number of specialist terms can evolve to support particular products; however the basic models are linear and easy to develop, [ARC 1996]. The life-cycle benefit is the benefit gained from the automation system. The life-cycle cost includes the initial investment costs and operational costs as shown in the example calculation below, [ARC 1996].

$$\text{Life-cycle Value} = \text{Life-cycle Benefits} - \text{Life-cycle Costs}$$

$$= \sum_{y=1}^{YEL} NPV\begin{pmatrix}\text{Annual Cost Saving} + \text{Annual Production Increases} + \text{Annual Yield Increases}\end{pmatrix} -$$

$$\left(\text{System Price} + \text{Initial Eng. Cost} + \text{Inst. Cost} + \sum_{y=1}^{YEL} \text{NPV}(\text{Annual Eng. Cost} + \text{Annual Ops. Cost} + \text{Annual Maint. Cost})\right)$$

Where YEL = Years of expected life of the system

NPV = Net present value

To remain competitive enterprises must continually improve the 'Life-cycle value' of their facilities. The author concludes that with the rapidly reducing 'Product life-cycle'[5] the automation systems that produce the end product must evolve in one of two directions:

1. The initial cost of the equipment including engineering must reduce significantly to allow facility disposal. It is often found in automotive manufacture that this method is uneconomic as mechanical systems have a natural life that extends beyond that of a single manufactured product.
2. To design flexible facilities that can respond to product change without significant disruption to production or investment cost. Understanding the manufacturing strategies and manufacturing technologies able to respond to these requirements is essential.

[5] Product life-cycle refers to the life-cycle of the end product produced by the manufacturing facility

2.6 The Role of Machine Control Systems in Supporting A Lean Manufacturing Strategy.

The primary areas where automation has a role to play in supporting lean manufacturing strategy are: Life cycle cost, the facilitation of workgroups, the introduction and use of flexible/agile facilities and the support of continuous improvement. Each of these areas are covered in the sections below.

2.6.1 Life-cycle costing of Control Systems

The principle phase of a Control Systems life-cycle as shown in figure 2-6 are: problem definition, design and development, application, operation and maintenance, reuse and disposal.

Figure 2-6 Control System Life-cycle Architecture

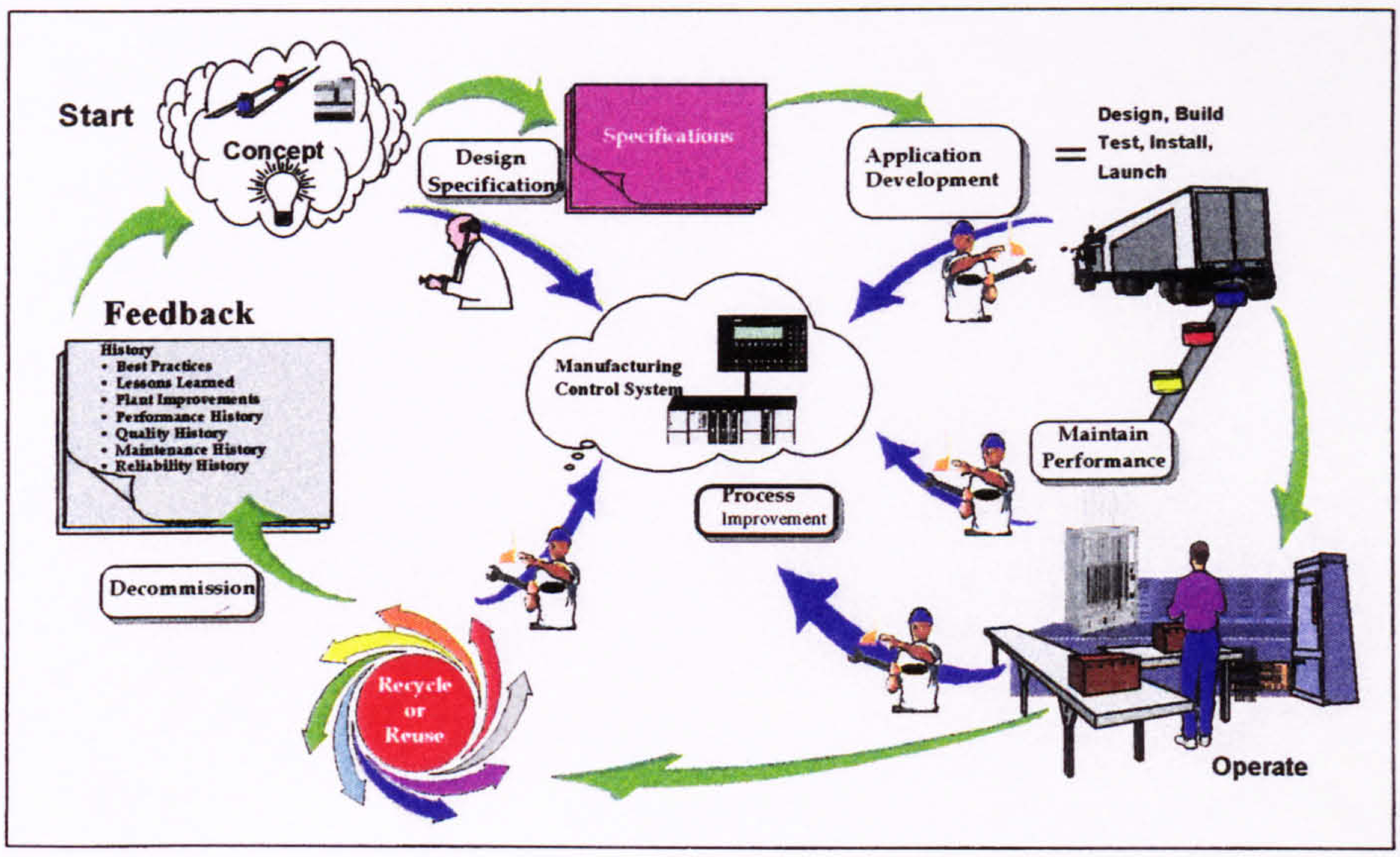


Figure 2-7 Life Cycle Value

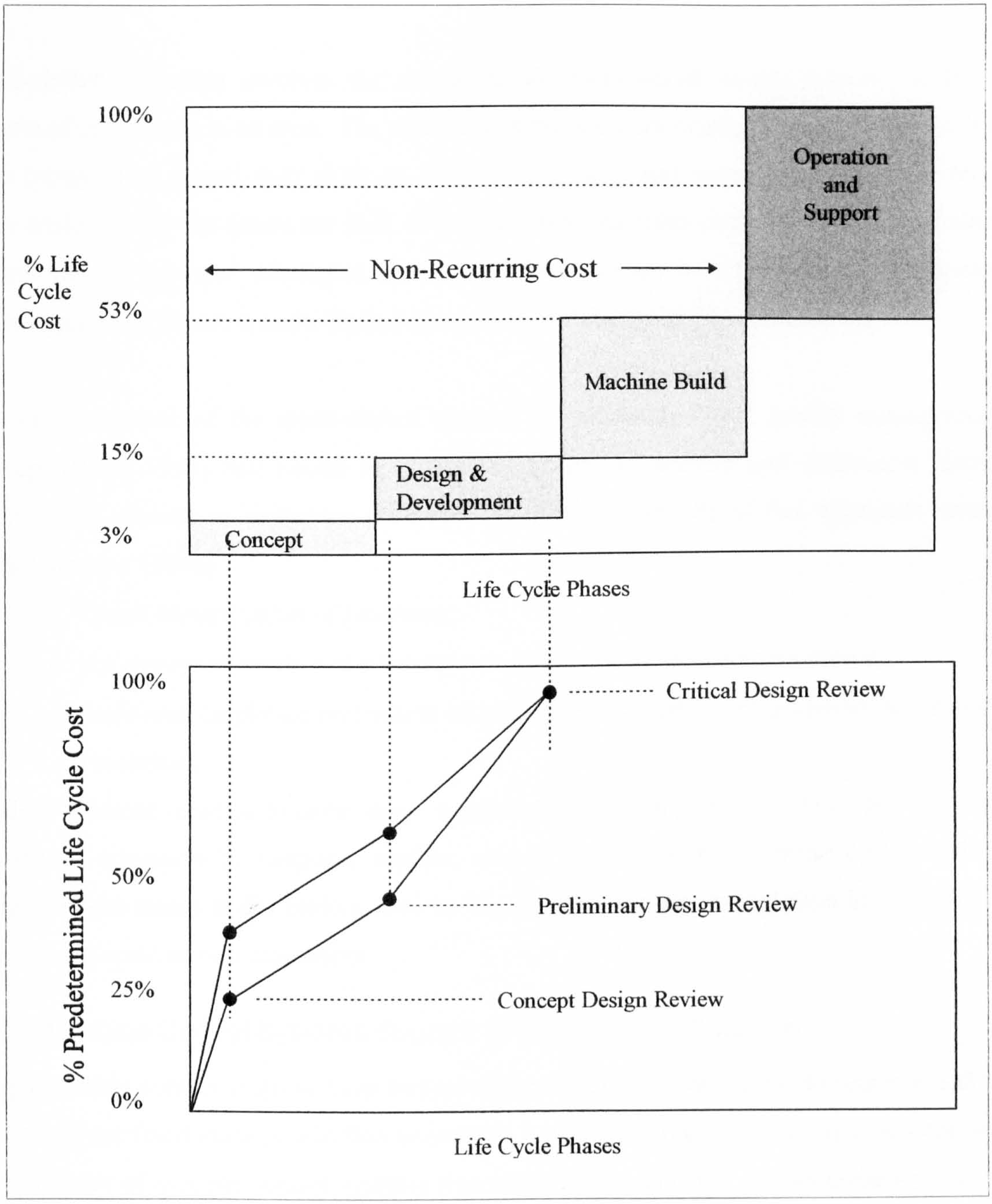
Control System Life Cycle Value =	*Life-cycle Benefits*	- *Life-cycle Costs*
	• Flexibility, • Agility, • Scalability, • Mean Time Between Failures, • Reusable Engineering. • Accuracy • Operational Effectiveness[6]	• Purchase cost, • Spare part cost, • Lead time, • Training, • Mean time to repair, • Support cost, • Configuration, • Complexity, • Specialist skill requirement.

All of the attributes shown are found in modern computer controlled automation. The attributes can be divided into two groups one for benefits and the other for costs depending on whether the attribute makes a positive or negative contribution to life-cycle costs. By focusing on these attributes and making demonstrable improvements significant benefit in operating efficiency can be made. Increasing life-cycle benefits and reducing life cycle costs shown in Figure 2-7 enhances life cycle value.

The SAE Life Cycle Cost model [SAE 1993] (Figure 2-8) identifies that although the *Concept Phase* represents just three percent of the total life cycle cost it is estimated that some twenty five percent of life-cycle cost is predetermined when the *Concept* is complete. Similarly some ninety five percent of life cycle cost is predetermined prior to the machines and equipment being built. Continuous improvement techniques employed in *lean production* may reduce this figure however a significant principle remains.

[6] Operational Effectiveness; - A measure of the ability of an AMT to integrate with the operating environment (i.e. multi-skilled teams) in particular manufacturing facility.

Figure 2-8 Life-cycle Cost Model [Adapted from SAE 1993]



2.6.2 Machine Control System's Support of Multi-skilled Work Groups

There are marked differences in working practices in different regions of the world (e.g. North America, Europe and Japan). Traditionally each shopfloor worker had considerable skill in a specific trade for example: electrician, mechanical fitter, and machine operator. This Trade Union led culture created strict demarcation between the tasks each tradesman undertook. The author concludes from personal experience of working in the North America Automotive Industry that these traditional working practices have remained largely unchanged, however, Japanese and the majority of European manufacturing plants have moved to multi-skilled work groups.

Multi-skilled operation involves the use of small 'empowered' teams responsible for all aspects of production in an area. The members of the team are normally trade[7] staff who have been retrained to extend their skills to encompass quality and operational issues as well as other trades' skills. In future the bulk of people emerging from company sponsored training centres will be 'process' orientated, armed with the necessary broad cross section of general skills required to fit into a multi-skilled production environment, [Training 1998].

The empowerment of the multi-skilled team is an important 'total quality management'[8] concept [Berry 1991] that allows individuals or groups to develop and implement ideas to improve the process or overcome problems. The major benefits of this approach include: [Schniederjans 1994a]

- Quick identification of problems,
- An increased number of solutions to quality and productivity problems,
- Improved employee motivation to participate in quality enhancement and problem resolution,

Modern machine control systems must support this changing environment; the one sided interest of engineers in technical aspects, should not result in the neglect of social and organisational issues and therefore lead to the creation and implementation of inadequately functioning systems or technologies.

2.6.3 Machine Control System's Support of Flexible/Agile Facilities

Programmable control systems have been a core enabler in allowing the automotive industry to move from fixed *mass production* to support a more flexible manufacturing environment. Key features of modern control systems that support this advance are: modular architecture and programmable functionality. Control systems capable of supporting agile production facilities will require the integration of more open systems, providing the opportunity to select specialist software and hardware. Next generation systems must allow the integration of other products from other vendors without the need to develop special programs, hardware or tools. Being as independent of the underlying technologies as possible.

[7] Trade staff: An employee that has served a recognized apprenticeship in an engineering discipline.
[8] Total quality management (TQM) - is a management concept that focuses the collective efforts of all managers and employees on satisfying customer expectations by continually improving operations management processes and products.

2.6.4 Machine Control System's Support for Continuous Improvement

The cascade affect on quality management tools and techniques (QMT&T) shown in Figure 2-4 identifies four areas where machine control system's can support Continuous Improvement (CI), namely: experience, resource, education and training. In each of these areas Control systems must match the skills required to support machine control systems with those available at the users site.

In addition control systems must provide information to allow the CI team to function. This will include predictive failure and performance information. A system that allows easy upgrade is essential to allow the team to take advantage of new technologies or processes.

2.7 Summary

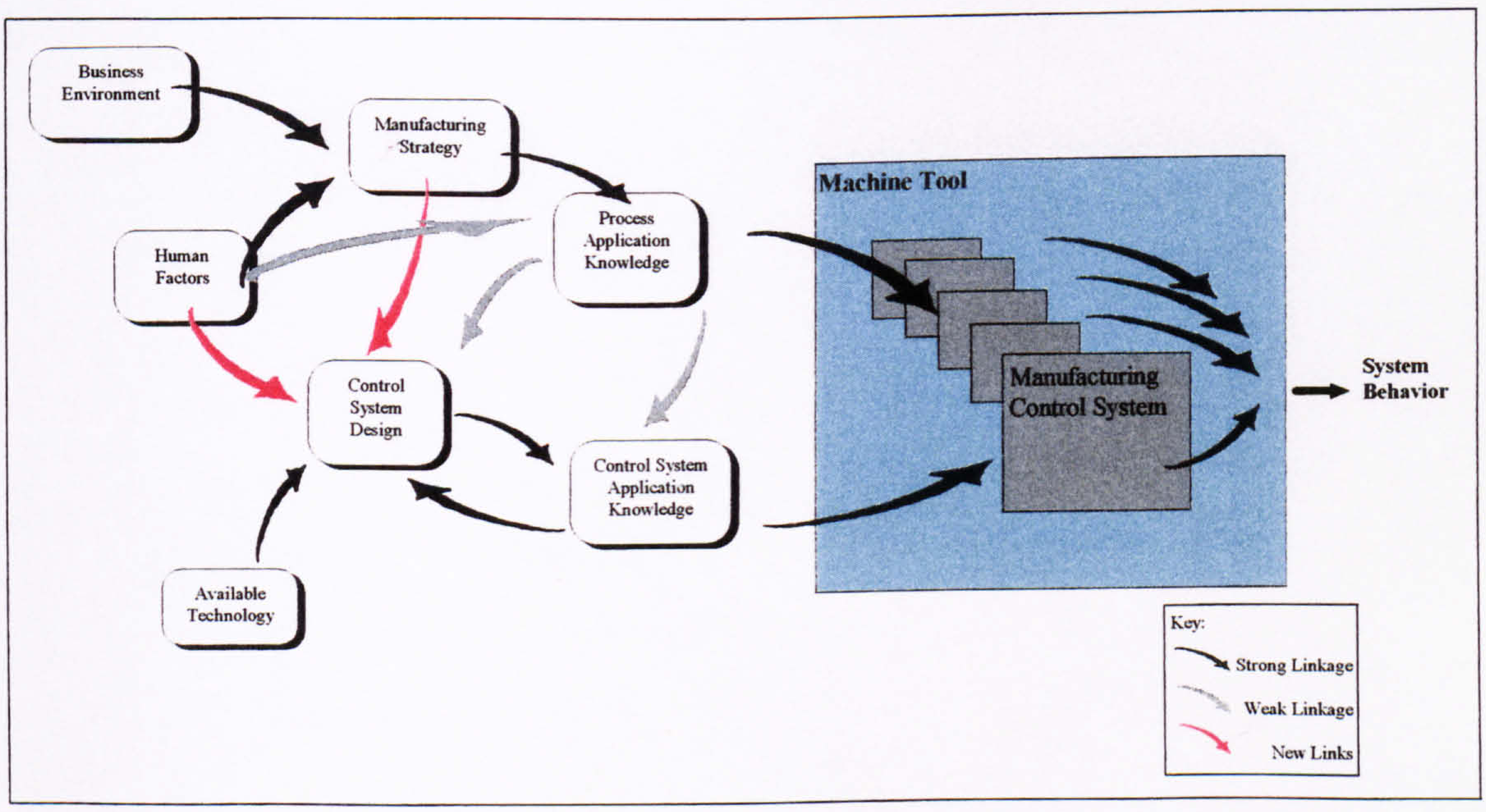
A paradigm shift has occurred in automotive manufacturing around the world. All the major automotive manufacturers are moving toward *lean* manufacturing techniques. This change requires new manufacturing techniques, fundamentally changing the processes and principles when compared to traditional *mass production. Lean* manufacturing techniques deliberately expose the production facility to market pressures. In contrast the nature of a *mass* production system demands that it be isolated from external demands to ensure the stability required by the system.

Mass production focuses on sub-optimisation, for example, considering only investment costs of individual machines when making decisions about capital purchases; optimising a single workstation without considering the broader systems costs and building in large batches to avoid the costs of changeovers. In contrast, *lean* manufacturing demands a systems perspective that focuses on creating a value-added flow through the elimination of waste. For example; three smaller machines feeding the assembly line with a batch size of one and quick changeover capability is a preferred option to one large machine that takes a long time to changeover and builds huge batches. The modern production system model must look beyond the activities in the production plant to encompass and support the manufacturing strategy.

From the study of contemporary Manufacturing Strategies in Automotive applications the author concludes that:

- Next generation control system (NGCS) design, development and implementation require a systems approach taking into account manufacturing strategy, technical, and operational requirements. This is particularly the case if the technology is to be introduced not only for its economic benefits but also for its strategic advantages.
- The NGCS must be closely aligned and play a key role in the enhancement of manufacturing strategy including life cycle cost, work practices and product and production agility.
- In order to produce an optimum solution the realisation of machine control systems needs to be considered from a number of viewpoints. The principle stakeholders and linkages are shown in Figure 2-9. Each linkage is colour coded to indicate the communication flow present in current control system development. The author concludes that some of the viewpoints are poorly integrated, demonstrate a lack of efficient information flow and use adhoc methods and tools for development. New links (shown in Red) identify the need for improved coordination between the Manufacturing Strategy, Human factors and the manufacturing control system design.

Figure 2-9 Communication Links between Autonomous Units



This chapter has established the role of manufacturing control systems within the context of a manufacturing system. Business requirements and the drivers of change have been discussed followed by a review of common manufacturing strategies and some of the tools used for manufacturing systems integration. The role of modern control systems in the enhancement of life cycle benefits and reducing life cycle costs has been established.

Chapter 3 will review current control system hardware and application software and discuss their effectiveness in a *lean* manufacturing environment.

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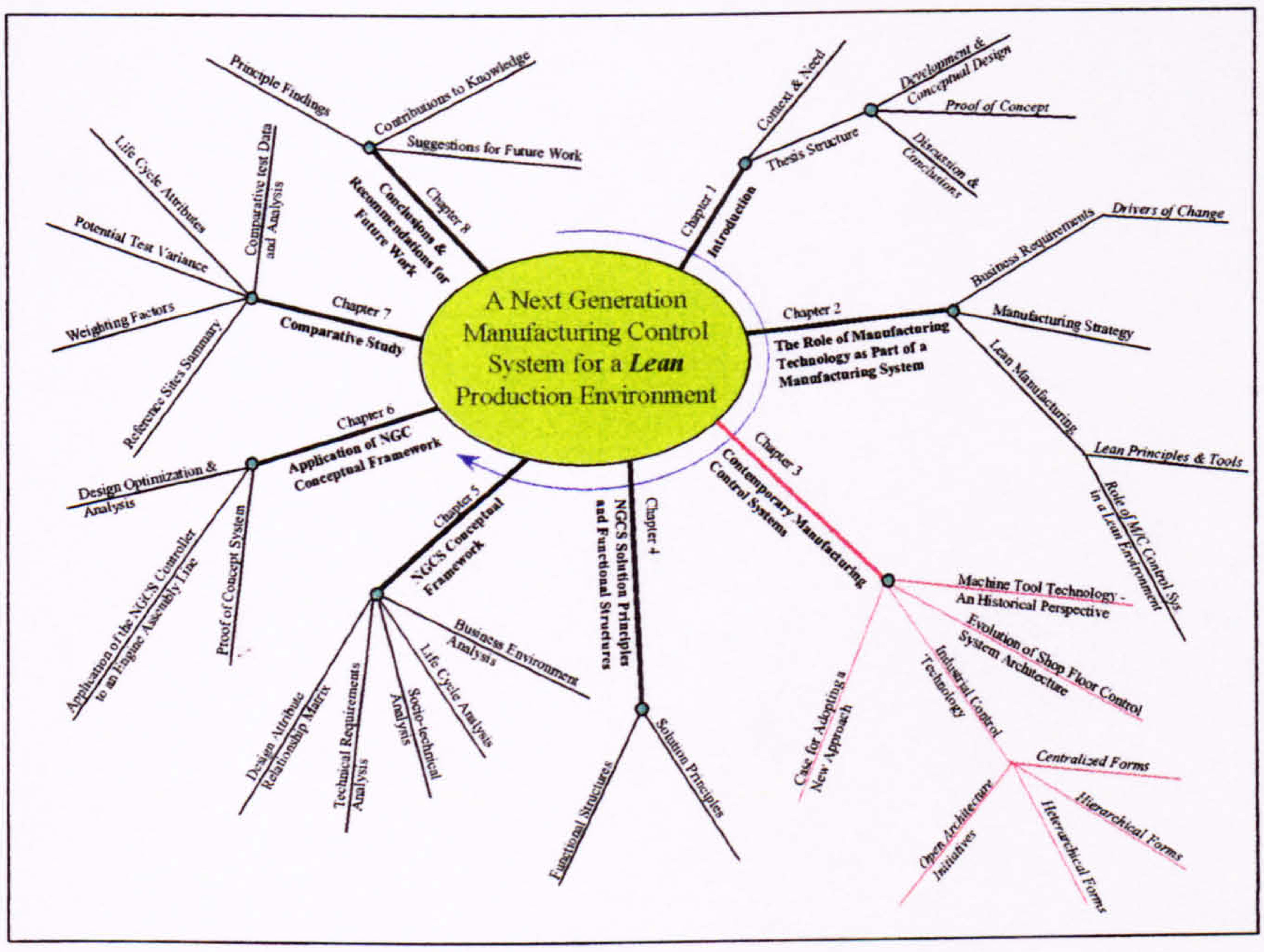
CHAPTER 3

CONTEMPORARY MANUFACTURING CONTROL SYSTEMS



3. Contemporary Manufacturing Control Systems

3.1 Introduction

Chapter 2 considered the evolution of business and manufacturing strategies from *Mass Production* to *Lean Manufacturing.* It described the role of machine control systems in supporting a *lean* strategy and considered structural attributes needed to assure an optimum NGCS design.

A prerequisite to the development of a NGCS design framework is a thorough interdisciplinary understanding of background concepts in: manufacturing methods utilised in the automotive industry, current manufacturing control system architecture, and emerging control technologies and strategies. This chapter will provide a brief history and background to the use of manufacturing automation in the automotive industry and go on to consider the evolution of control systems. Current industrial control technology and tools are reviewed in detail followed by a critique of current research effort and emerging trends. Finally implications and conclusions are drawn.

3.2 Machine Control Technology - An Historical Perspective

Machine control technologies have become invaluable in the operations of many different manufacturing industries, [Powers 1987]. As with many other industries the Automotive machine tool industry is *pulled* by end user demands for higher overall equipment effectiveness (OEE) and quality. At the same time it is also *pushed* by technological and process development in electronics and other related domain technologies.

The origins of machines that allowed the introduction of *mass production* can be traced back to the later part of the 19th century. The Frenchman Theophile Gramme first demonstrated an electric motor driving a machine at the Vienna Exhibition of 1873; however, the immense possibilities of the electric motor in the machine shop were not recognised for over 20 years. It was not until just prior to the First World War that use of auxiliary motors and electrical switching components to drive the feed motions of machine tools became widely available, [Rolt 1986] [Woodbury 1972].

In the early days of the automobile industry the availability of reliable electrical power and new *mass production* ideas led to the belief that machines, rather than hand work could provide a more appropriate means of achieving the required component part and product uniformity. Specialised single-purpose machine emerged that reflected the division of labour as well as providing *self-acting* or semi-automatic machines [Batchelor 1994].

With the invention of the vacuum tube and transistor, it was possible to build machine control systems that to a limited degree could be programmed; thus allowing the production of high volume product variants. A significant breakthrough was made in 1947 with the invention of the numerical control (NC) at the Massachusetts Institute of Technology. The NC allowed the machining of complex low volume parts, [Rembold 1994].

In 1968 engineers from the General Motors Corporation laid down a set of design guidelines for a product that became widely known as the Programmable Logic Controller, (PLC) [Warnock 1988].

The guidelines provided by General Motors required that the controller must be:

- Easily programmed and reprogrammed, preferably in plant, to alter its sequence of operations.
- Easily maintained and repaired - preferably using plug-in units.
- more reliable in a plant environment *(than existing relay technology)*,
- smaller than its relay equivalent,
- cost competitive, with solid-state and relay panels then in use.

In June 1969 the earliest fully programmable controller was delivered to the General Motors Hydramatic Division by a consulting engineering company called Bedford Associates. The first system was called the 084 being the result of the eighty fourth iteration of the development process, [Kissell 1986]. Bedford Associates changed their name to Modicon and went on to develop a number of new models before Gould Inc. purchased them in 1978.

Modicon were not alone during these early years. Allen Bradley had been working on a solid state control system for some time. Their first solid state control system, the PDQ was designed in 1959. It could not be reprogrammed as easily as the PLC, but fulfilled a demand as a relay replacement system. Allen Bradley responded with a system called a programmable logic controller (PLC[9]). Even though the General Motors plant did not choose the Allen Bradley controller, it went on to become a successful, reliable system.

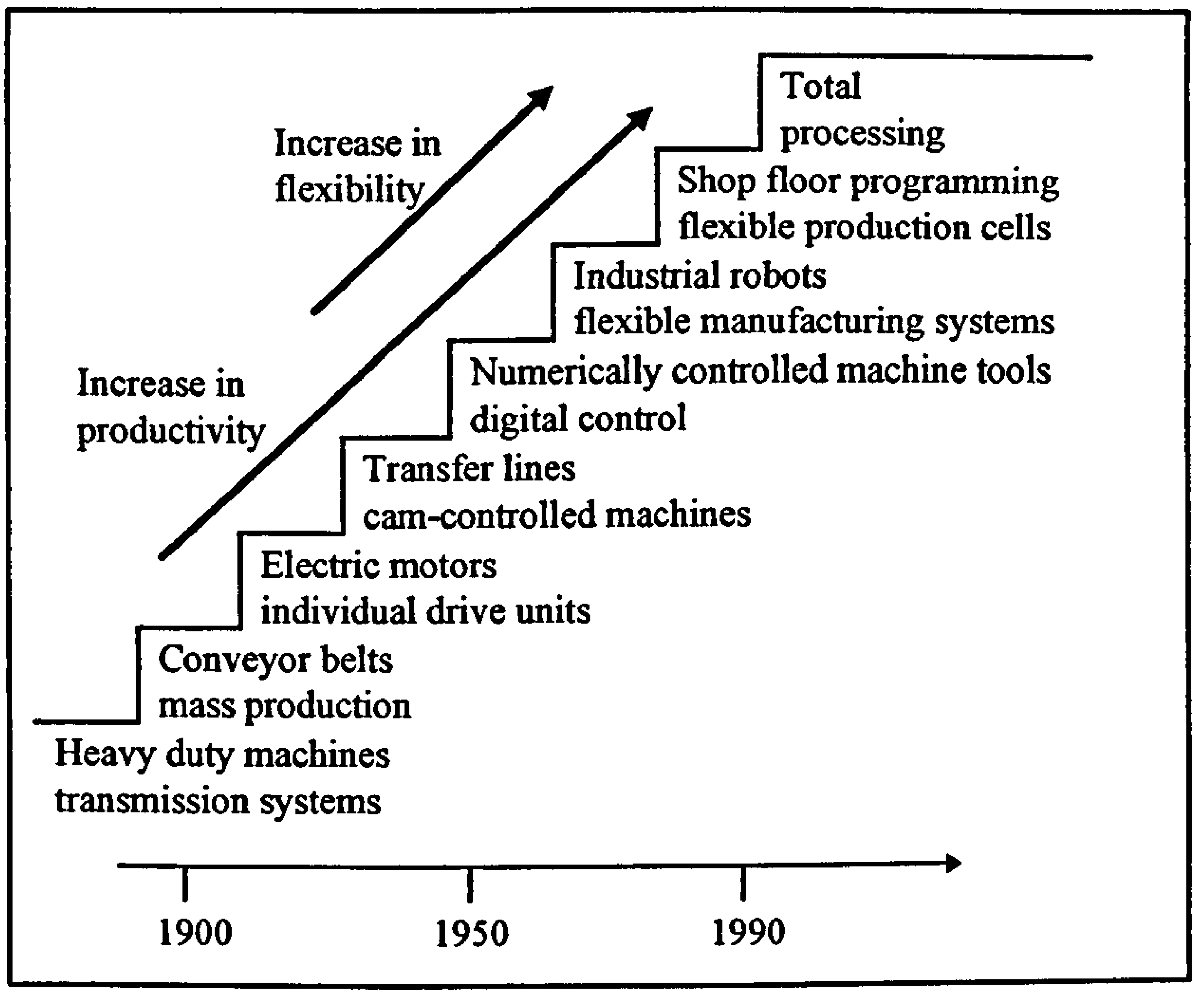
As PLC technology became generally available in the early 1970's the automotive industry was one of the first major industrial sectors to utilise the systems in large quantities. For this reason, commercially available PLC systems were heavily influenced by the requirements of the automotive end users and their machine suppliers. The original specification for PLC systems, and the lack of suitable communication technologies led to the PLC being used as a relay panel replacement system for a number of years. The development of ladder logic as the main stream programming language reflected end user requirements for systems that mimicked the JIC electrical drawing format used in North America. The centralised suite of panels that once housed the relays was replaced with a centralised PLC architecture.

In recent years improvements in PC hardware and software performance have made PC-based systems viable for real time applications traditionally dominated by the PLC. Adoption of the PC platform preserves the application software investment by allowing a degree of portability not found in proprietary PLC systems. An additional benefit was the low cost compatibility with standard operating systems, networks and user interfaces. Such systems are usually implemented as *Soft PLC's* where software loaded onto the PC provides PLC like functionality.

[9] To avoid confusion with the term 'personal computer' (PC) the abbreviation PLC will be used throughout to refer to any programmable controller system. PLC is a trademark of Allen Bradley.

The significant machine control developments outlined are summarised in Figure 3-1.

Figure 3-1 Development Stages in Manufacturing Technology [Wernecke1993].



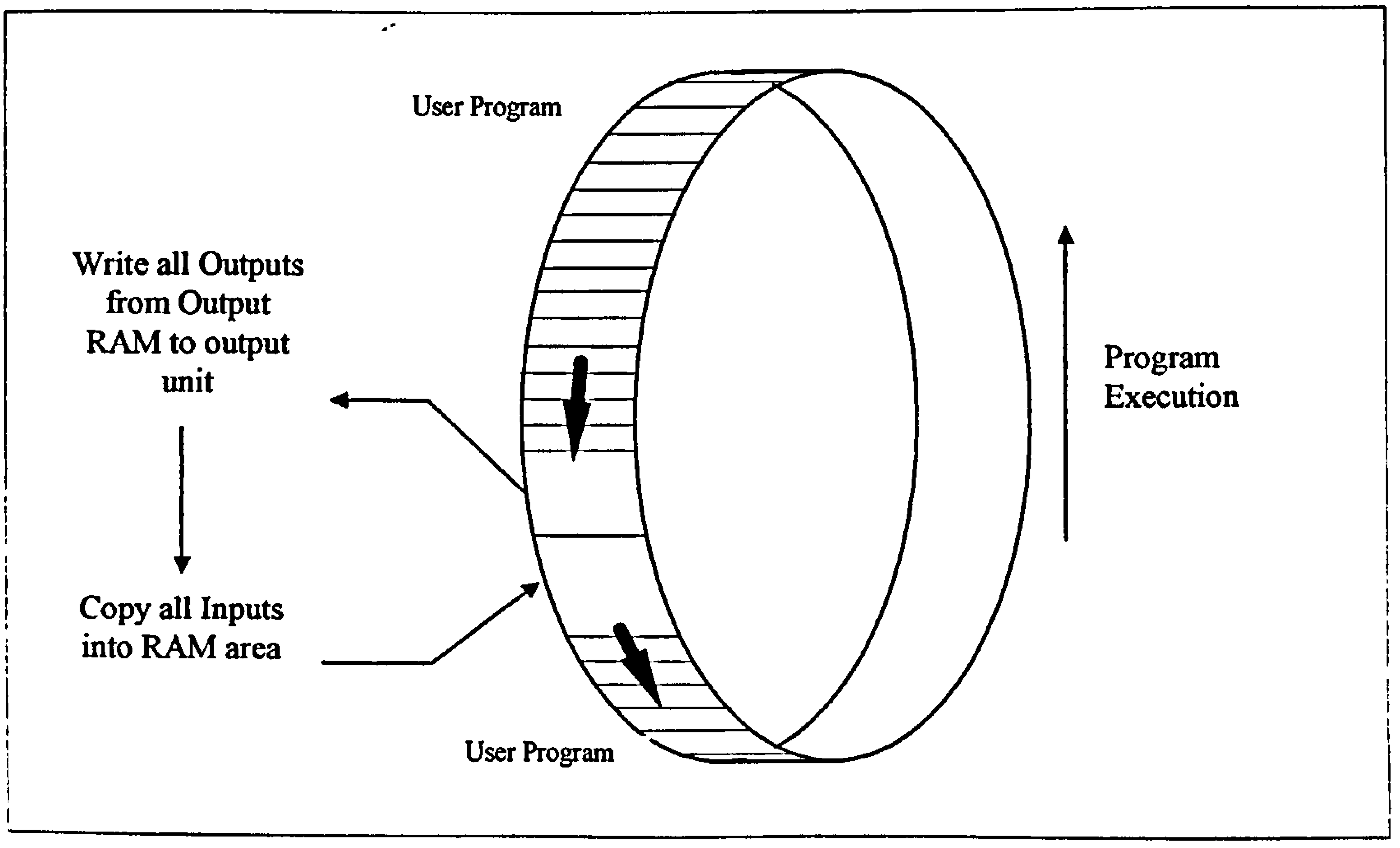
Industrial Control Technology

The domain considered in this section is the sequence and interlock control of machines and part transport automation in discrete parts manufacture. The application focus is on automated machining and assembly applications (e.g. engine and gearbox components and their assembly) at relatively high volumes (typically 100K - 500K units per year).

3.2.1 PLC System Hardware

The PLC is responsible for monitoring the workcell, reacting to events and enforcing device behaviour based on the current control strategy residing in its program logic, [Lauzon 1996]. In most PLC's the input/output handling and the program logic are processed in a scan based manner as shown in Figure 3-2 below. Workcell monitoring is achieved by reading the input image table. The input data is applied to the application program and device behaviour set by changing the state of the variable in the output image table, [Campbell 1996]. The PLC then changes the value of the corresponding output addresses. The time for one complete cycle is known as the scan time. On automotive machines it is desirable to keep this time under 60 milli- seconds as longer scan times increase the potential of missing an input signal making the machine unreliable, [Brown 1994] and introduces excessive logic processing delays.

Figure 3-2 Cyclical PLC Scan [Warnock 1988].



PLC products can be placed into one of five categories using their Input and Output capability as a basis for segregation: These are:

1. Micro PLC - <100 Inputs and Outputs,
2. Small PLC - 100-256 Input and Outputs,
3. Medium PLC 256-1024 Input and Outputs,
4. Large PLC - >1024 Input and Output,

Frost & Sullivan report that in 1995 the PLC market in Europe amounted to £1.013 million [Frost 1995]. Their report predicts that the market will grow at a compound rate of 5% with a value of £1.426 million by 2002. The market is dominated by a few global suppliers including: Siemens, Groupe Schneider, Allen Bradley, Mitsubishi and Omron.

The Micro and Small sectors of the market are very price sensitive. Intense competition is evident, particularly from Japanese suppliers who pursue aggressive pricing policies. Processing speed and memory capacity are climbing continuously without significant rises in price. Micro and Small PLCs are being introduced with performance requirements which until recently were only found on *large* PLCs. Most now offer some form of proprietary networking; however the predicted arrival of IEC1158[10] and EN50170[11] is likely to lead to suppliers producing systems which are compatible with these emerging international fieldbus standards, [Jowers 1996].

The majority of Small PLC's are now able to offer some form of motion control. Accurate point-to-point control is possible; however some of the more advanced features, for example linear or circular interpolation are not provided. A variety of display systems can be used, however because of the limited input/output capability small line display systems are normally sufficient to control the application.

Within the automotive industry the application of *micro* systems has been limited. Far more use has been made of the Small PLC. In their simplest form they have been applied to sections of automation (part transfer) and assembly machines. The greatest benefit has come from their application as station controllers networked together as shown in Figure 3-9.

[10] IEC1158 - High Efficiency Communication System standard.
[11] EN50170 - Field Bus Standard, High Efficiency Communication System

The application of Medium size PLC's on new automotive projects has dropped significantly over the last ten years. The systems themselves are continuing to grow in power with the majority able to offer extensive network, memory and input/output capabilities. Most have integrated personal computers available. Without exception all the major suppliers are able to offer extensive NC and CNC control via proprietary plug-in modules.

The increased functionality of the Micro, Small and Medium PLC sectors has led to the elimination of the Large PLC from the majority of automotive project specifications. Their use is now predominantly in process based applications and industries. It is reported that the PLC is now closing the gap on the Distributed Control System (DCS) traditionally seen as the ideal solution in the process industry [Rohrmann 1995]. The large PLC can now offer access to PID loops, SCADA and process management systems. The integrated PC capability allows the use of CASE tools which provides a natural language design environment for control and management functions; open system networks for system communications, remote intelligent device connectivity and management information system integration. A typical PLC in this sector of the market will integrate three levels, shop floor, supervisory and management using three major components: process PLC hardware at a controller level which combines sequence logic, floating point maths, PID loop control and complex functions; UNIX based real time process management system integrating PLC supervisory functions, intelligent alarm handling, operator interfaces, recipe and data handling; and a management data system.

The automotive machine tool industry is *pulled* by end user demands for higher overall equipment effectiveness (OEE) and quality. Although not widely used, advances in microelectronics have led to the practical feasibility of redundant elements in the control system, that will detect a failure and allow the process to continue to the end of the shift, or shut down in a controlled way chosen by the designer, so avoiding costly damage [Marcos 1995].

As rival PLC suppliers draw closer in terms of hardware and pricing; application software and support issues are becoming important differentiating factors. Not only are the selection criteria for suppliers becoming nebulous, the systems themselves are changing. It is unclear how much longer the terms distributed control system (DCS), programmable logic controller (PLC), PC, and supervisory control and data acquisition (SCADA) system can be meaningful system differentiators.

3.2.2 Open Architecture Initiatives

Modern PLC's utilize standard microprocessors combined with a proprietary real time operating system (RTOS). The RTOS is the Kernel of code that controls all operations and tasks run on the microprocessor. PLC's provide fast deterministic and reliable control by building the control engine around the RTOS. In recent years there has been a significant amount of research and commercial development dedicated to the introduction of RTOS's for the PC architecture, [see Appendix A]. To obtain the same level of deterministic control a PC must use the same type of hard real time operating system with capabilities beyond normal PC operating systems (e.g. Microsoft™ Windows). The principle claim for this type of system is that it facilitates the design of high performance systems by integrating the best production technologies from different vendors, and the gradual enhancement of system performance by allowing the progressive introduction of new hardware and software elements into existing control systems at affordable cost, [Zbigniew 1996].

Today many control system manufacturers are offering their new products as in some way being *Open*. According to the IEEE definition "an open system provides capabilities that enable properly implemented applications to run on a variety of platforms from multiple vendors and coexist with other systems applications" [Zbigniew 1996]. This clearly infers that only systems that follow common vendor-neutral conventions can be described as open systems.

The author summarises the goals for the specification of open system architecture to be: interoperability, portability, scalability and interchangeability. Interoperability enables system components to be designed independently and then integrated with components from other vendors. Portability allows system components to operate on different platforms. Scalability is a feature, which enables the customer to increase or decrease the functionality of a system by changing the number of components and/or upgrading or downgrading specific components. Interchangeability allows substitution of one component with another due to its capabilities, reliability or performance.

Harrison provides a broader business view by stating that next generation control systems must be based upon products which are designed independently, and can then be integrated with other products from other vendors without the need to develop special programs, hardware or tools. The system must be fully documented, freely available, managed and promoted by a multi-national independent body. Independent certification of conformity will be required to ensure end user confidence [Harrison 1996]. Flexibility is achieved by having autonomous subsystems that are relatively self-contained, along with the characteristic of incremental development [Kaula 1998].

A major issue for researchers in this area apart from reducing complexity is to break the dependency between machine controllers and their application software development. For example, it must allow machine tool builders to re-use much of their generic software engineering and yet accommodate many of the end users' specific standards. Machine tool builders must be able to efficiently move from a job in Germany using company A's equipment, to another in North America using company B.

3.2.3 OMAC White Paper

In December 1994 an "Open Modular Architecture Controller (OMAC)" white paper was published by a group of engineers from North America's three largest automotive producers. The document outlined their views on the requirements for open modular control systems in the automotive manufacturing industry, [Chrysler 1994]. The report also highlighted numerous problems related to the use of proprietary controllers that, while presented from an automotive viewpoint, are common to many other industries. The control system requirements outlined in the OMAC report have been summarised and categorised into system and sub-system requirements in tables 1 and 2.

Table 1: Overall system requirements specified by OMAC

OMAC System Requirements
Meet all safety, reliability, robustness and environmental requirements.
Satisfy government and company standards.
Provide multi-vendor solutions.
Easy upgrade without the involvement of controller suppliers.
The use of components/tools available in the general purpose computer industry.
Intuitive and user friendly to reduce training expenditure.
Support scalability by adding, removing or replacing units.
Present a common user interface environment across all applications.
Be deterministic.
Multi-level security access procedures.
Provide a controller infrastructure that gives flexibility for integration of user proprietary technologies.

Table 2: Sub-system requirements specified by OMAC

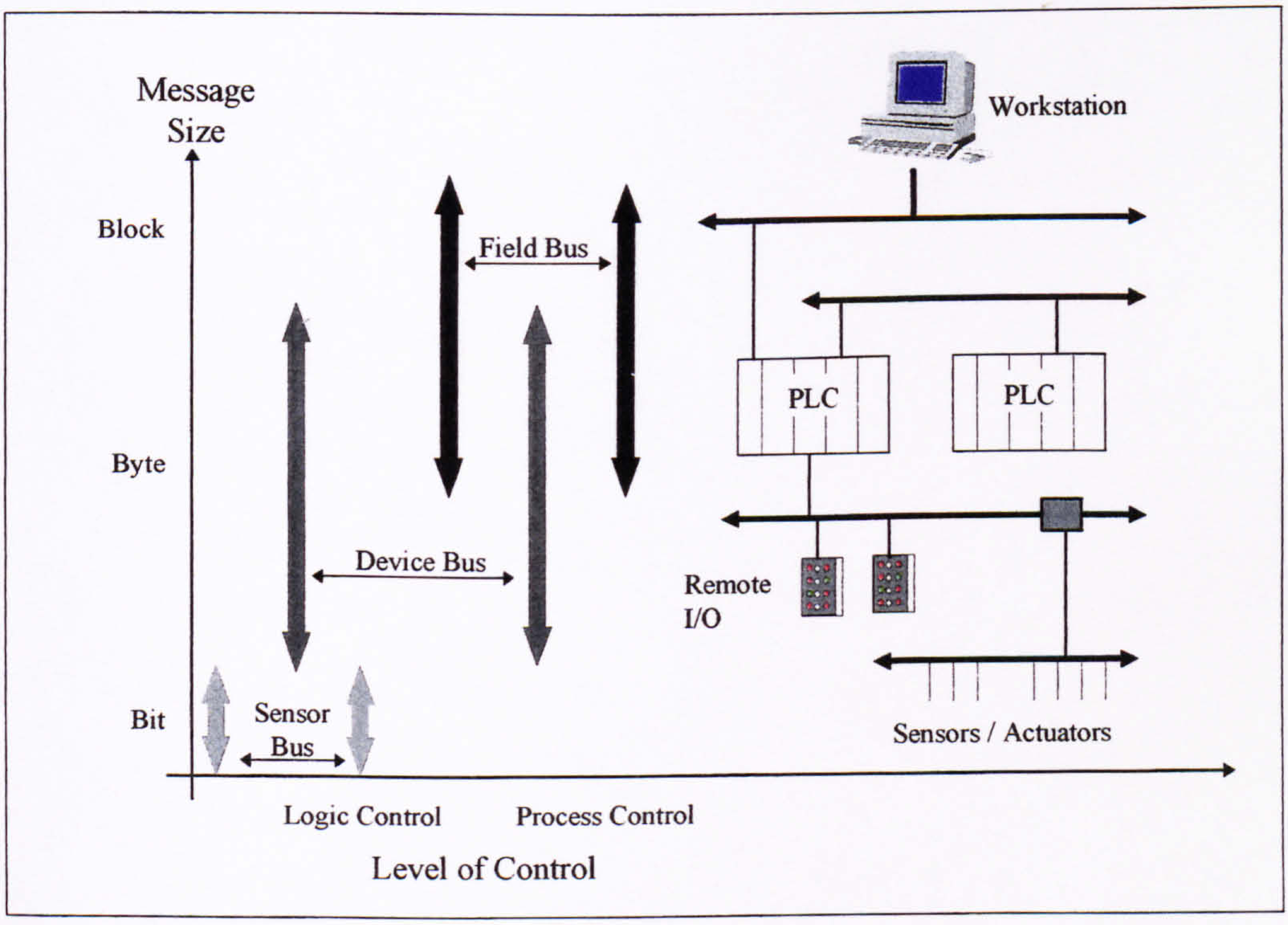
OMAC Sub-System Requirements	
External Interfaces	Allow connection to the upper business management layer using off the shelf components.
	Provide an interface to various real time bus systems (for the connection of inputs and outputs) with minimal cost and effort.
	Integrate diagnostic capabilities for both the controller and machine.
Internal Architecture	Provide flexibility to allow control designer to select the most appropriate system kernel for a particular application
	'Plug and Play' concept through the use a standardised Application programming Interface layer.
	Common real time system database.
	Controller hardware bus structure to be a 'de facto' standard, for example VME, ISA, EISA or PCI.
	The controller architecture must support standard output to servo drives, either digital or analogue.
	The control of the servo amplifier must be able to reside within the drive amplifier or OMAC.
Human Machine Interface (HMI)	Controller must support a commonly accepted graphical user interface environment, for example Microsoft Windows.
	The run-time version of the HMI must be available separately without the associated development system at a substantially lower cost.
	The HMI must have the ability to interface with other elements in the controller using a 'well accepted' messaging scheme, such as DDE in the Windows environment.
Application Software	Sequential control software to be written in IEC1131/3 or a flow chart style.
	The controller must support standard part programming inputs, such as RS-274D.
	The motion control editor should reside on the same platform as the HMI.
	The discrete event controller programming software will reside on the OMAC.

3.2.4 Serial Bus Systems

There is a clear trend in many industrial sectors toward the use of intelligent decentralised systems. Distributed automation concepts demand a means by which the physical flow of fragments of information can be realised between systems that need to communicate, [Scheer 1991]. Previously proprietary communication architectures and customised protocols have prevailed. However, in recent years open standardised communication systems have gained widespread acceptance, [Busby 1990], [Roesler 1996].

Industrial control networks are characterised by the transmission of data as opposed to voice, and video (as well as data) carried on business networks. Device and control networks typically support a relatively small number of devices and provide a deterministic response. The main differences between D*evice* and *Control* networks lie in the areas of message size, cost per node and the speed of the network, [ARC 1995].

Figure 3-3 Industrial Networking Structure



The layers within the standard automation system hierarchy have in recent years typically reduced from a five-layer system (plant, centre, cell, station and device) to the present three-layer system, (information, control, and device). Recent developments raise the possibility in the future that Ethernet (or a similar technology) may be used at the control and sections of the device layers; producing a two tier network infrastructure. Determinism can be achieved by protecting portions of the plant network through the use of smart router technology [Benoit 1996].

The demand for direct information exchange between different system elements, has led to extensive research in the area of communication standardisation, [Judge 1988]. Some examples of the more important standardisation and research efforts in this field are: ISO/OSI Standards and the ISO/OSI Reference Model, [Judge 1988], EN50170 Field Bus Standard, High Efficiency Communication System Standard IEC1158 and the SERCOS IEC1491 standard that provides a protocol designed specifically for communication between controllers and drive systems, [Hibbard 1996].

3.2.5 Manufacturing Control System Software

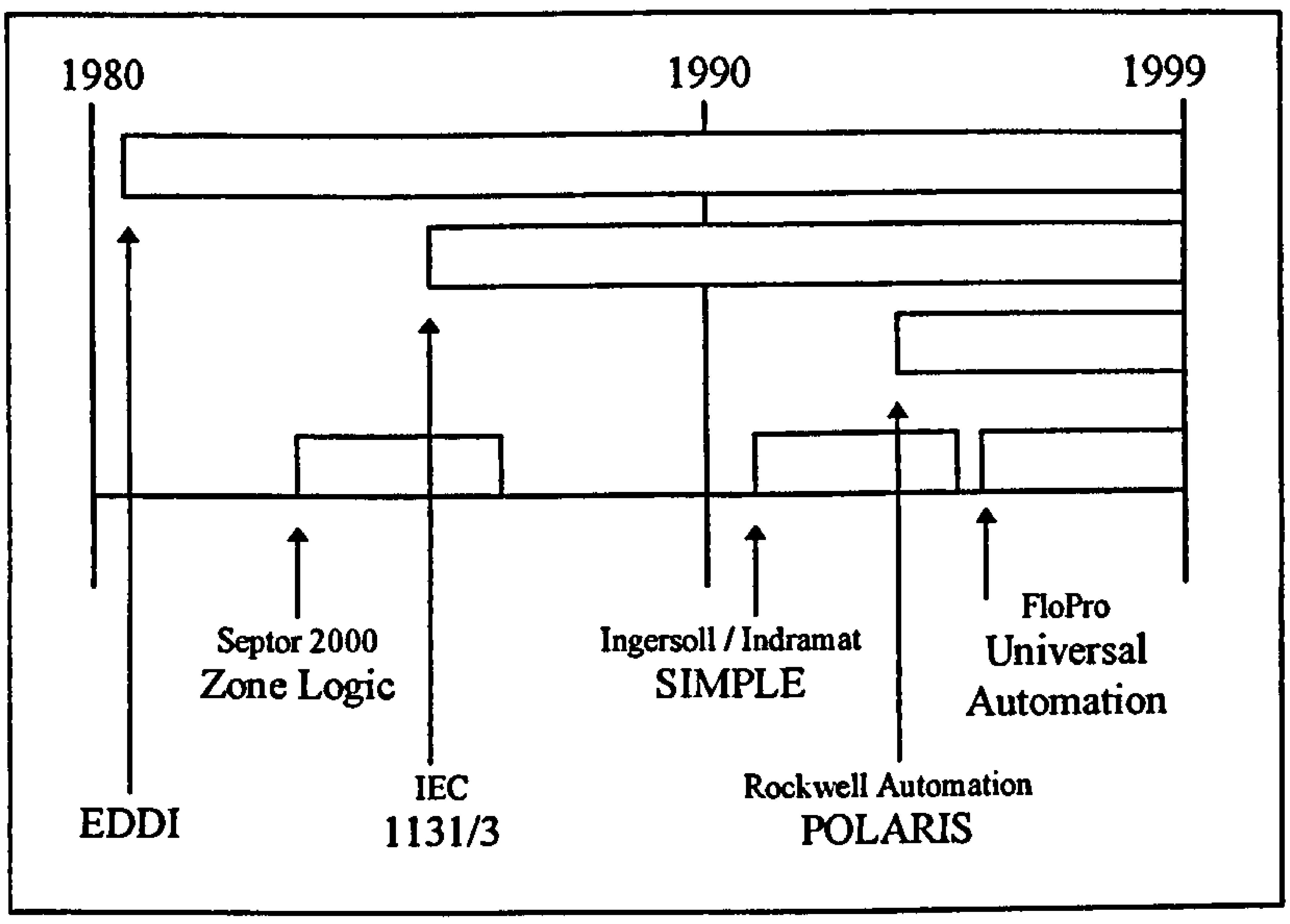
The size and complexity of some software application programs has led to considerable research into structured methods of programming [Ready 1991]; and the verification of programmed PLC code [Moon 1994]. This section identifies the most significant initiatives and research projects that have shaped automotive manufacturing control system software.

The number of control system hardware options presented to a specifying engineer has increased significantly in recent years. For many years the selection process centred on a hardware cost/functionality analysis between different PLC hardware suppliers. Following the selection process the end user was then locked into that vendor's application software and programming methods. However, recent initiatives toward standardised programming tools (IEC1131-3) and the acceptance of P.C. based controllers, (softlogic PLCs) [Gyorki 1996] has greatly increased choice.

Basic PLCs run a single language (normally ladder logic) whilst other, more sophisticated products run five or more languages at the same time in order to satisfy the IEC1131-3 standard, (see 3.2.5.1). The use of *open* platforms has led to third party companies entering the market with specialised languages attempting to fill niche markets. The most significant of these new languages that have influenced the automotive industry include flow chart, natural language, and process development languages.

Each programming language has a different level of intrinsic structure that will ensure a common approach between different machine tool builders. Ladder logic and Statement List languages have virtually no structure and hence require a comprehensive specification to obtain uniform structured code. In contrast process development languages (e.g. Polaris[12]) have a regimented set of rules built-in and therefore require only minor definition to ensure a common approach. Figure 3-4 provides a time line indicating the introduction and use of the different systems.

Figure 3-4 Application software Time Line.



3.2.5.1 PLC Programming Standard IEC1131/3.

IEC1131 is the International Electrotechnical Commissions standard for PLCs. A working group within the IEC was set up in 1979 to look at the complete design of PLC's, including hardware design, installation, testing, documentation, programming and communications. The working group assigned with the task (IEC65B/WG7) established a number of specialist groups to develop different parts of the standard, [Lewis 1995], [Gyorki 1996]. The five major parts are shown in Figure 3-5.

[12] Polaris :- Polaris is a trade name of the Rockwell Corporation.

Figure 3-5 Parts of the IEC Standard [Lewis 1995].

Part	Title	Contents
Part 1	General information	Definition of basic terminology and concepts.
Part 2	Equipment requirements and tests	Electronic and mechanical construction and verification tests.
Part 3	1993 Programmable languages	PLC software structure, languages and program execution.
Part 4	1993 User guidelines	Guidance on selection, installation and maintenance of PLCs.
Part 5	Message service specification	Software facilities to communicate with other devices using communications based on MAP manufacturing Messaging Services.

Part 3 of the standard specifies application software used to develop and maintain programs. The standard provides for a set of three graphical and two textual languages (see Figure 3-6): instruction list, ladder diagram, sequential function charts, function block diagram and structured text. Programming packages using IEC1131 are available in two basic forms: as proprietary code for use on a single platform or in the form of a soft PLC[13] that whilst utilising a dedicated real time kernel, is able to operate on a number of widely available *open* platforms.

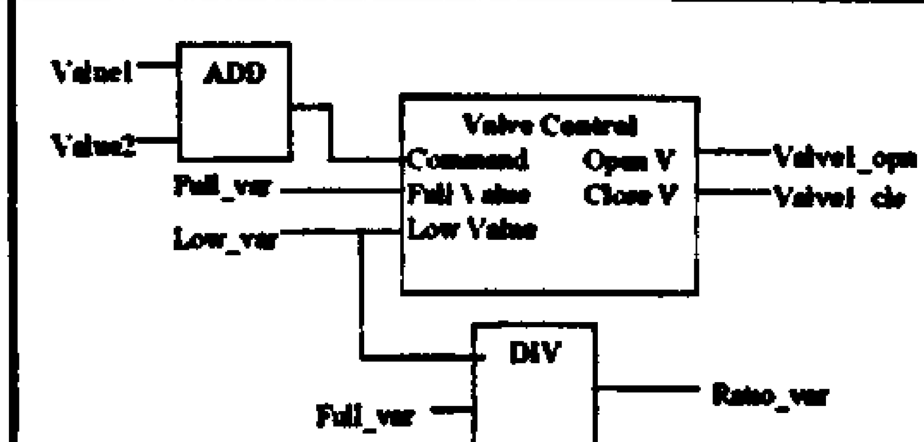
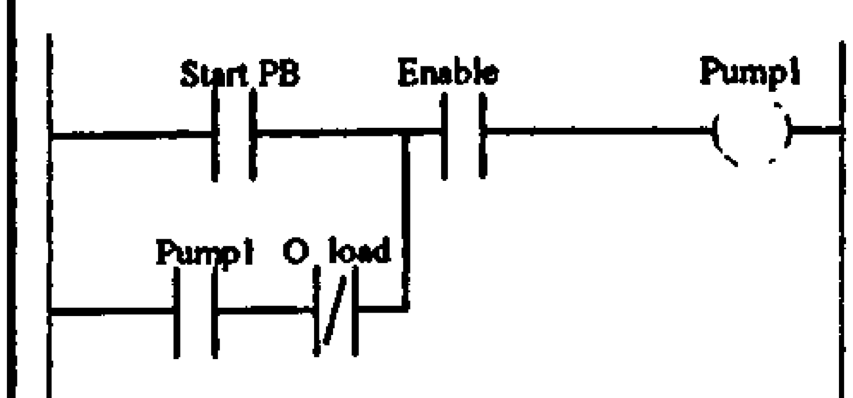
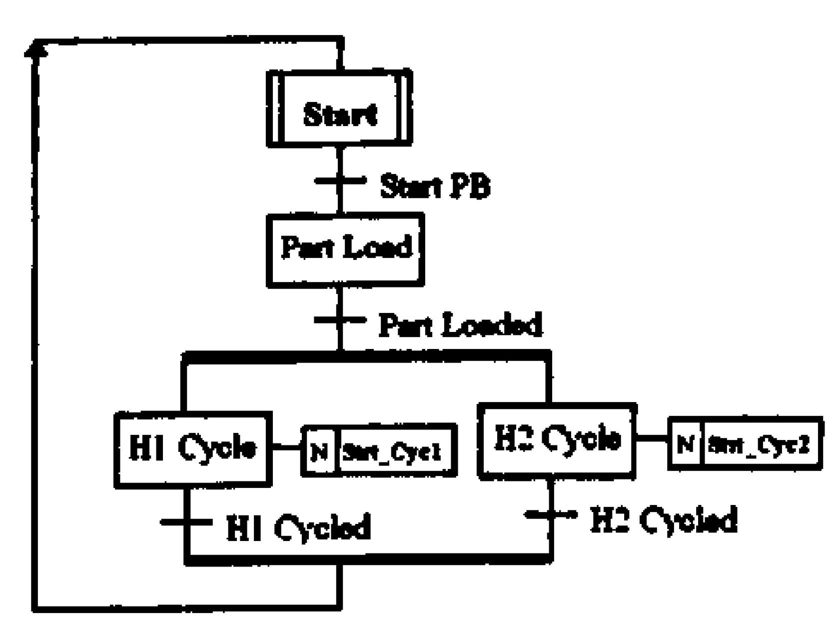
The program designer is (in a fully compliant system) free to choose the language that is most suitable to solve different sections of the control problem. A number of key elements are common throughout the five languages, to ensure that programs are interoperable and can be readily ported to different systems. The key areas include: character set, identifiers, language keywords, data types and variables.

[13] Soft PLC :- trade name. Teledenken U.S.

Figure 3-6 IEC1131 Section 3 Languages.

Language	Description	Example

Structured Text	A high level textual language that encourages structured programming. The language syntax closely resembles PASCAL.	IF TANK4 > 50.4 THEN
		Valve1 :=ON;
		ELSE
		Valve1 :=OFF;
		END_IF;

Instruction List	A low level assembler style language based on similar languages found in a wide variety of contemporary PLCs.	LD %IX20 AND Valve2 JMPNC Lab6 ST Tank_level
Function Block Diagram	A graphical language for depicting signal and data flow through functional blocks. The blocks are re-usable software elements.	
Ladder Diagram	A graphical language based on traditional JIC relay ladder logic diagrams. The most commonly used language in the Automotive industry.	
Sequential Function Chart	A graphical language for depicting sequential behaviour of a control system. Used to define control sequences that are time and event driven.	

To increase the awareness and use of the IEC1131 standard, PLCopen (a product independent association) was formed in 1992. One of the primary objectives of the association was the development of a certification process. The certified levels are:

- Base level: defines a limited sub-set of the IECstandard.
- Portability level: this level provides for the exchange of function blocks or functions between different manufacturers programming systems. The exchange is based upon a neutral file exchange format.
- Full compliance: products complying with this level are able to exchange complete applications.

The standard is gradually being enhanced through the publication of technical papers. An example of this is a Function Blocks (FB) library designed for the purpose of driving axes via the IEC 1131-3 programming languages [PLCopen 1997]. These gradual enhancements to the standard and end user pressure for more *open* control systems has led to the majority of PLC suppliers conforming (or having plans to conform) to the IEC1131 PLC standard.

3.2.5.2 EDDI

EDDI is an acronym for Error Diagnostic Dynamic Indicator and has been the most widely used supplier independent programming structure in the Automotive Industry. EDDI was a European initiative led by a Ford Engineer in the Body and Assembly Division in the U.K. The concept was originally conceived in 1981 and is still in wide spread use today. In their European operations Ford, Jaguar, Rover and General Motors apply various forms of EDDI however all contain the same basic principles. Ford instructs their machine tool builders in the technique and insist they attend a training course prior to writing control code for their machine tools.

The EDDI concept is an application software structure in its purest form i.e. it does not require special hardware or software and can be applied on a variety of PLC and PC based software platforms. It can also be applied within the constraints of the IEC1131/3 specification.

The EDDI philosophy pioneered a number of major achievements including:

- The first non proprietary software structure for use with PLC systems,
- A documented system that could be specified by end users and taught to operators, maintenance staff and if necessary machine tool builders,
- A mapped sequence making the *process* apparent to the operator,
- Fully integrated diagnostics. I.e. the diagnostics are an integral part of the sequence control program,
- The realisation of manual diagnostic capability known as *manual cross interlock checking.*

3.2.5.3 Zone Logic

In 1984 a major U.S. machine tool builder in the Automotive industry (Lamb Technicon), acquired a 20% interest in a small Texas based electronics company called Septor Electronics. Lamb directed Septor's research and development toward finding ways to improve the productivity of the transfer machine equipment that it supplied. This research led to a patented control philosophy called Septor 2000.

The goal was to develop a control scheme that could analyse the condition of the machine, automatically trap machine fault and compose error messages without the need for a programmer to have anticipated the fault. In addition the system would be able to indicate the actions available to the operator in manual mode and give the reason why the other buttons were inhibited. The technique employed was termed 'Zone Logic'.

The designers at Septor considered the main problem with conventional machine control to be that engineers must program the control system for every possible situation and define the sequence of every step to be accomplished which quickly evolves into many thousands of lines of code. Malfunctions under this system are often missed initially as it was impossible for the programmer to have anticipated and provided error routines for the thousands of possible failure modes. Crucially this led to the diagnostics being developed during the initial production period when they were most needed. A consequence of this strategy was that operators lost confidence in the ability of the system to accurately diagnose problems.

The concept that set Septor 2000 apart from other system of its time was the ability to 'tell the machine what to it *could* and *could not* do, set the machine its goal and leave the system to decide how to do it'. The valid conditions of each device were entered into the system and the current conditions were then compared during operation to the possible valid conditions. Any condition detected that did not match an entry in the table was invalid and an error message automatically generated.

Roberts compares the system to a series of still photographs, [Roberts 1989]. The Zone table equates to the set of still photographs. The Septor 2000 control system was the camera taking a film of each mechanism in real time, and finally the Zone Logic compared the current image of the mechanism with the photographs. If the images matched the system was okay. If the images did not match, the differences were highlighted and presented to the operator.

Several other features made the system an important milestone in machine control including: distributing the control to a station level, connecting the controllers via a fibre optic bus and integrating numerical motion control into the architecture were all innovative concepts at the time.

Unfortunately Lamb's controlling interest in the early days restricted the market for the controller with other rival machine tool builders refusing to use the system. In June 1988, the controllers biggest customers the U.S. Automotive industry lost interest when a subsidiary of Daimler-Benz, the manufacturers of Mercedes Benz automobiles gained a controlling interest in Septor.

3.2.5.4 SIMPLE

The Chief Control Engineer[14] at one of Lamb's rivals in the machine tool industry; Ingersoll Milling Machine Company presented a paper at the 21st ESD Annual International Programmable Controller Conference titled; 'The SIMPLE Approach to Transfer Line Control'. The paper outlined a programming technique designated as 'Sequential, Integrated Motion and Process Logic Educator', (SIMPLE). The aims and eventual achievements of the concept mirrored those laid down eight years earlier by the design team at Septor.

Although the aims were very similar some of the strategies for achieving them were different. The similarities included the requirement to integrate motion into the system instead of the contemporary practice of adding motion as a poorly integrated 'optional extra'. The principle

[14] Chief Control Engineer, Ingersoll Milling Machine Company : - Thomas P. McDunn.

of a modular design approach was also similar promoting the idea that a controller should be placed at each workstation and then networking the controllers back to a co-ordinating controller that synchronised part flow. The major differences were seen in the way that individual mechanisms were controlled. SIMPLE unutilised a defined sequence making the sequential process the top layer of the control definition and promoting a tabular process overview to the operator, [McDunn 1992].

A German controls company, Indramat[15] developed the concept in conjunction with Ingersoll. The result was a product based on the SIMPLE concept called TRANS 04. The TRANS 04 was unsuccessful in the market for many of the same reasons that the Septor system failed. However the TRANS 04 had the added disadvantages that it was dedicated to sequential processes and heavily focussed on a particular segment of the machine tool market; transfer machines. The product was hindered by modularity problems making it impossible to use on more complex single purpose machines and too expensive to be used for automation and simple machines [Lomax 1998].

3.2.5.5 Flow Chart Programming

General Motors Powertrain Division (GMPD) in conjunction with a small software house called Universal Automation pioneered a software programming tool based upon classical flow diagramming and designed to execute on a standard PC platform.

Flow chart programming provides a flexible toolkit for the programmer with no formalised structure. The lack of an inherent structure gives the technique very few advantages over Ladder Diagram although some argue that the language lends itself more naturally to sequential flow and as such is easier to understand. Following GMPD's experience on the Romulus program General Motors have now started to lay down a set of rules for use with flow diagram programming in a similar way that EDDI acts a structured set of rules for Ladder Diagram.

Despite its application on over 500 machines in General Motors the automotive industry is doubtful as to the benefits. A report compiled by the Advanced Manufacturing Group in Ford Motor Company recommended not to move to FloPro[16] now, but to continue with present

[15] Indramat is a division of the Rexroth Corporation.
[16] FloPro :- trade name. Nematron Corporation. U.S.

controls policy for major programs,[Hyrilla 1994]. Chrysler and the European manufacturers are also playing a waiting game, having no large scale implementations planned.

Another language that claims the same advantages as graphic flowcharts is called 'Natural Language Programming'. A program is made up of a number of tasks. Within each task are several 'states'. The code is tailored for machine control therefore its supporters claim that it is more intuitive and understandable than common computer or machine language. No major automotive program has used the technique.

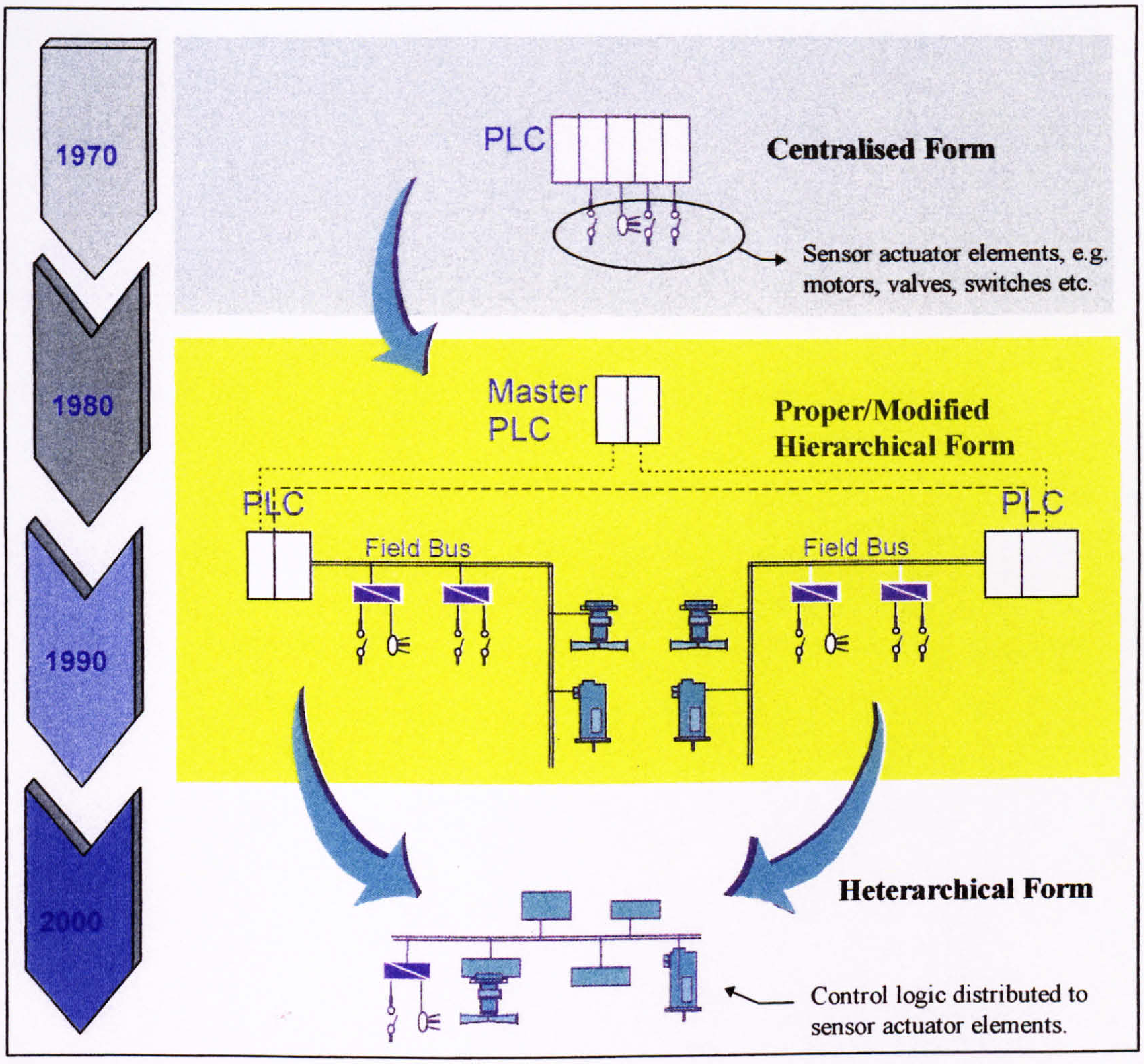
3.3 Evolution of Shopfloor Control System Architectures

Automotive manufacture encompasses a wide range of machining, welding, fabricating, process and assembly technologies. This varied application requirement leads to a wide range of control system complexity. At one extreme are discrete systems with simple sequential code. At the other end of the scale large complex systems can be found capable of process and data manipulation with fully co-ordinated multi-axis motion. The rapid advances in computing and communication technology have made possible a large number of possible architectures.

The author's study of several automotive plants reveals that by correlating control system architecture against the age of machines, a trend from a centralised, to a progressively more distributed architecture is evident. This leads to an increase in the autonomy of control elements and hence a reduction in the processing of accumulated data at a central point.

Dills et al, note this evolutionary increase in the autonomy of control elements in the research domain by describing four control forms, they are: a 'Centralised form, Proper Hierarchical form, Modified Hierarchical form and Heterarchical form, [Dilts 1991].

Figure 3-7 Evolution of Control Forms [Adapted from Dilts et al. 1991]



3.3.1 Centralised Form

In the centralised form represented in all control elements are concentrated at a single point. Normally the electrical power supply systems are placed adjacent to the controlling elements along with the safety systems. The only partial distribution is hydraulic and pneumatic elements that rely on close proximity to the actuator for satisfactory performance. In the late 1970's the first industrial communication networks led to the sequence controllers' input/output system to be placed at the cell or station level. A significant reduction in the length of cable runs was achieved, however from an architectural perspective the system remained a 'centralised architecture'.

3.3.2 Proper Hierarchical Form

The requirement for increasing machine accuracy and reliability inherently drives ever more complex solutions and the need for effective diagnostic systems. Improvements in serial bus technology designed for use on the shop floor facilitated the emergence of the 'proper hierarchical form' as shown in Figure 3-9.

The representative machine shown consists of a number of machining heads positioned on both sides of a part transfer system. The centralised PLC is replaced with a number of small PLCs controlling discrete sections of the machine. Each section is then linked via a real time serial network back to a co-ordinating controller. This distribution of the control elements facilitates standardised design of cells or machining stations, and a standardised transfer mechanism. Engineers are able to commission individual heads before the machine is complete reducing lead-time. Hardware savings are minimal; however investment saving is expected from the modularisation of hardware, application software and documentation. Significant complexity benefits are realised via the standardisation of machine control software including: [Victory 1997]

- Smaller less complex application software, making maintenance easier,
- Reduced processing load (scan time) on an individual controller[17],
- System scan time (including serial communication) of less than 20 milli-seconds,
- Greater program modularity and reusability.

The Chrysler Corporation in North America utilised this modular construction of machines and control systems to complete the final stages of construction on their factory shopfloor [Wicksted 1997]. The machine tool builder (Giddings & Lewis) built and tested individual machining heads in their factory and then shipped the completed modules to the Chrysler automotive manufacturing facility for final assembly. Normally the units would have been built up into a complete machine on the machine builder's shopfloor tested and then stripped back to their modular form for shipment. Eliminating this activity makes considerable time and cost savings.

[17] Reduced from typically 60 milli-seconds with a centralised controller architecture, to 5 milli-seconds on each of the distributed PLC's.

3.3.3 Modified Hierarchical Form.

Heterarchical elements are being progressively introduced into control system architectures to improve performance; however the vast majority of these systems can be classed as modified hierarchies since this remains their predominant structure. In many applications the Proper Hierarchical Form acts as messenger between two cell or station controllers, adding no value to the data. Galbraith noted that serious delays started to occur as cell controllers wait for the upward transmission of information and the response to be downloaded from the master controller, [Galbraith 1973]. The use of vertical master/slave relations combined with peer to peer relations between cell controllers characterise the modified hierarchical form. Practical automotive applications include, machining stations with direct gauging feedback from the adjacent station.

Figure 3-8 Centralised Form

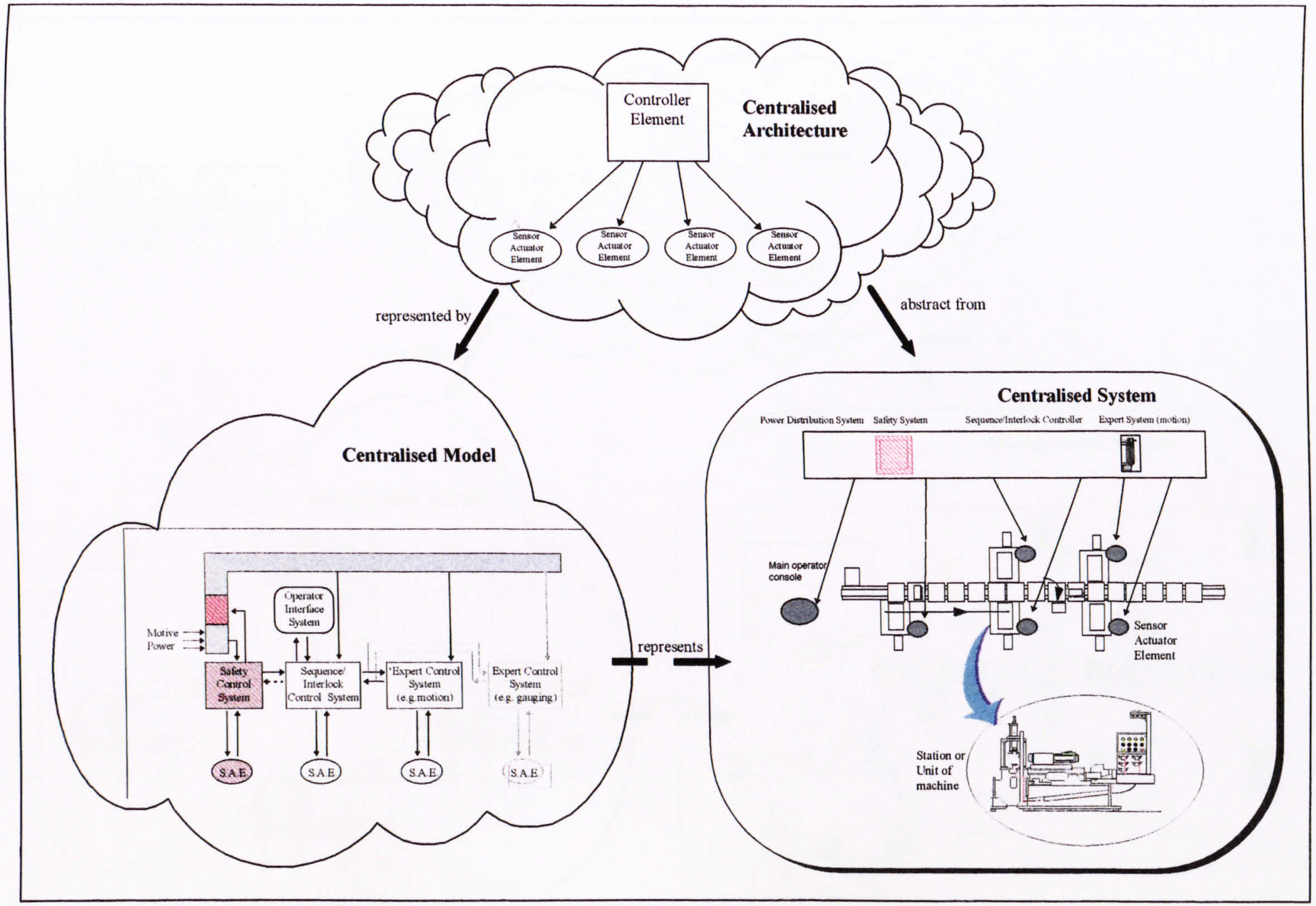
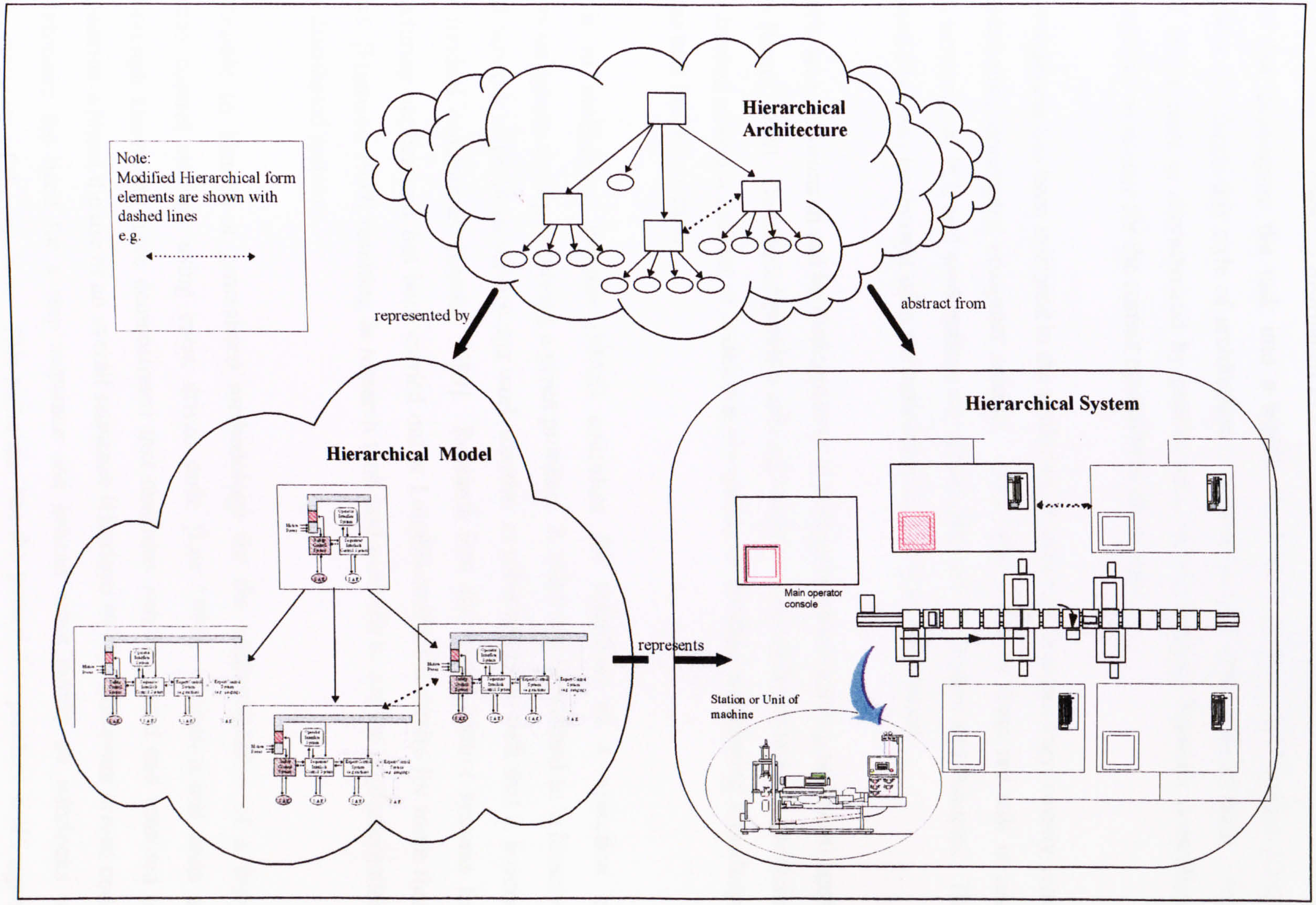


Figure 3-9 Proper/Modified Hierarchical Forms



3.3.4 Heterarchical Manufacturing Architectures

Considerable research effort [Gausemeier 1998],[Luntz 1995],[Gausemeier 1995], is now focused on taking the partially distributed PLC systems shown in Figure 3-9 and developing concepts that decompose the task into a highly distributed artificial intelligence (DAI). Throughout this thesis this style of architecture is referred to as a Heterarchical form. This style of architecture is characterised by peer-to-peer, lateral relations between controllers, which requires no *master* for the correct operation of the system.

This development has been mirrored in the evolution of information technology; twenty years ago, mainframes dominated computer science. Now only a few of them are still in use. Instead, networks of PCs and workstations are spread over offices, homes and factories. The centralised PLC may be thought of as the mainframe of industrial automation.

Two main areas of research can be distinguished: distributed problem solving and multi agent systems [Bond 1988]. Distributed problem solving considers how different tasks or problems can be divided among a number of nodes that co-operate in dividing and sharing knowledge about the task and its solution.

Research in multi-agent systems (MAS) considers the behaviour of a collection of autonomous agents aiming at solving a given problem. A MAS can be defined as 'a loosely-coupled network of problem solvers that work together to solve the given task that is beyond their individual capabilities' [Durfee 1989]. Research into distributed control systems for manufacturing applications has been carried out at Loughborough University for more than ten years, [Harrison 1998] resulting in research tools and methods to aid the implementation of fully distributed systems.

It is possible to identify a generalised methodology for the implementation of a fully distributed control strategy using event driven code [Lee 1996]. Experimental tests at Loughborough University have demonstrated that machines can be cycled and returned to initial position without the use of an overall sequence [Harrison 1998]. The event driven code used eliminates the need for a step sequence and instead relies purely on interlocks to constrain elements of the machine. This technique has the potential to produce multi agent systems that self optimise to the most efficient cycle. If a fault occurs causing an element to slow down, (e.g. due to an oil leak in a cylinder) the sequence of operations has the potential to automatically re-optimise and automatically change the machine cycle. Node scan time is negligible due to the small amount of embedded code however network speed is a critical factor.

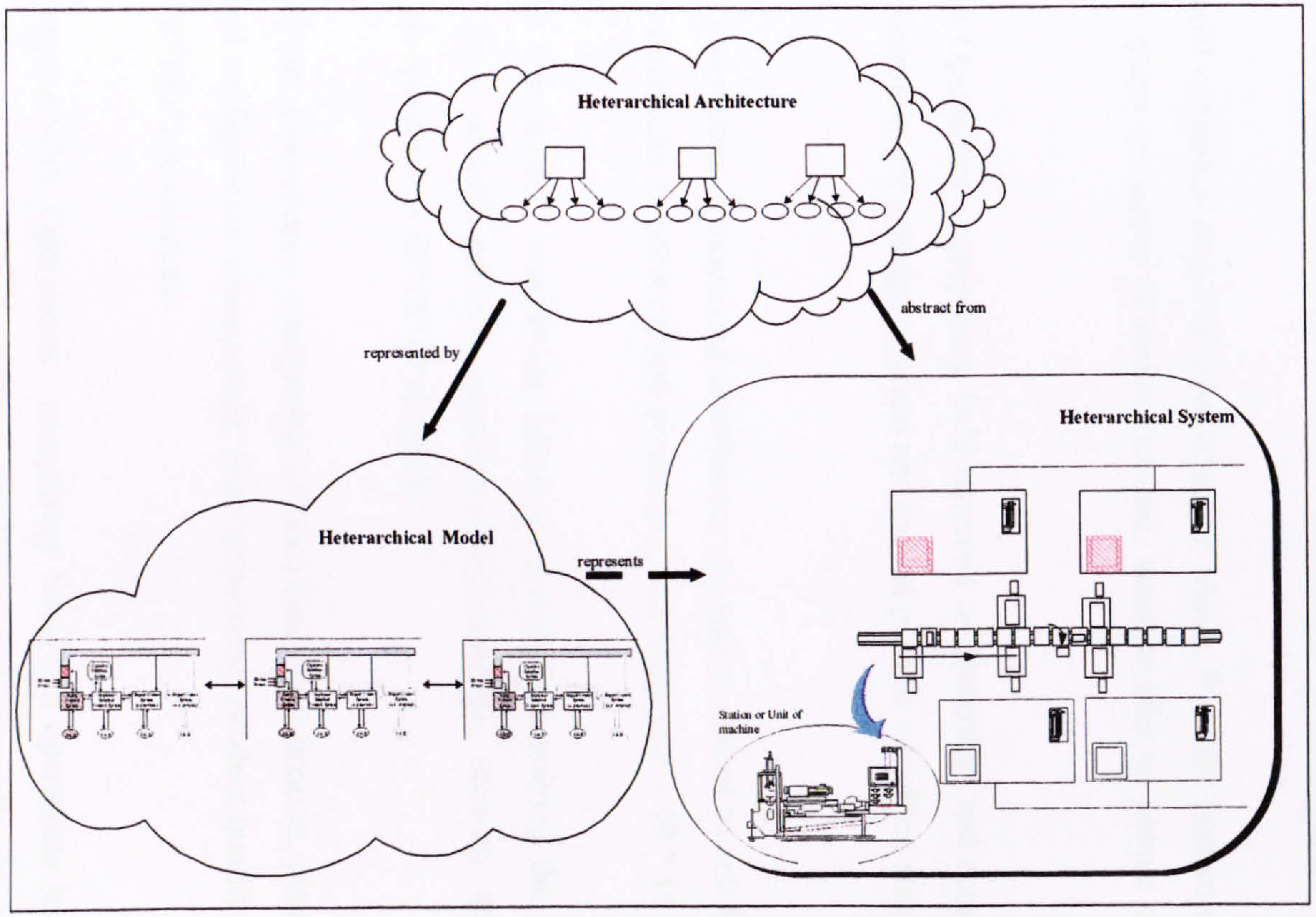
Embedding tried and tested software into a standardised node greatly increases the predefined code, and to a large extent eliminating the need for the end user to program equipment. The system will instead, require the elements of a machine to be identified and then linked for automatic and manual operation. This will facilitate the use of process focused development languages that eliminate the translation process that occurs when the Controls Engineer converts the mechanical timing charts into machine logic. In conclusion it can be shown that DAI has a number of potential benefits including [Lee 1996], [Gausemeier 1998] :

- Improved machine reliability through the use of tried and tested code,
- the potential to build redundancy into the node allowing improved system availability and predictive failure,
- simplified maintenance and support the use of multi-skilled labour to operate and maintain the production facility,
- accurate life-cycle prediction[18].
- the replacement of sequence programming with interlock definition,
- improved scalability and flexibility.

At the time of writing very few inherently Heterarchical systems are evident in industry, and to the author's knowledge none in the automotive industry. Limited examples can be seen in textiles, [Tlon 1998] the semiconductor industry [Semi 1998] and building automation [Echelon 1996].

[18] Accurate Life-cycle prediction: With the control device being embedded into an actuator the manufacturer should be able to predict the life of the actuator based on its application/duty cycle and automatically warn the operator of failures.

Figure 3-10 Heterarchical Form



3.4 Practical Shopfloor Control System Models

Elsag Bailey identifies an integrated command, control, and communications model based on extensive practical experience in the design, manufacture and deployment of industrial control systems [Jensen 1993]. Although his experience is mainly in the domain for continuous and batch automation, the platform and application enterprise model (EBPA) can be equally be used to define sequential or discrete manufacturing enterprises.

The EBPA model comprises of a five-level structure which, from the bottom up, is defined in terms of the *spans of control* of various entities, whether they be people or automation [Bayne 1995]:

Level 0 - Field Operations: comprising field-mounted measurement and actuation devices and the local controllers for selected physical and logical process variables; state space size ~ 10 elements.

Level 1 - Unit Operations: comprising InterDevice operations related to cell level machine controls, safety interlocks, or other critical processes; state space size ~ 10 * 10 elements.

Level 2 - Area Operations: comprising InterUnit operations involving the planning and execution of area control polices, manufacturing planning, start-up and shutdown sequencing, state space size ~ 10*10*10 elements.

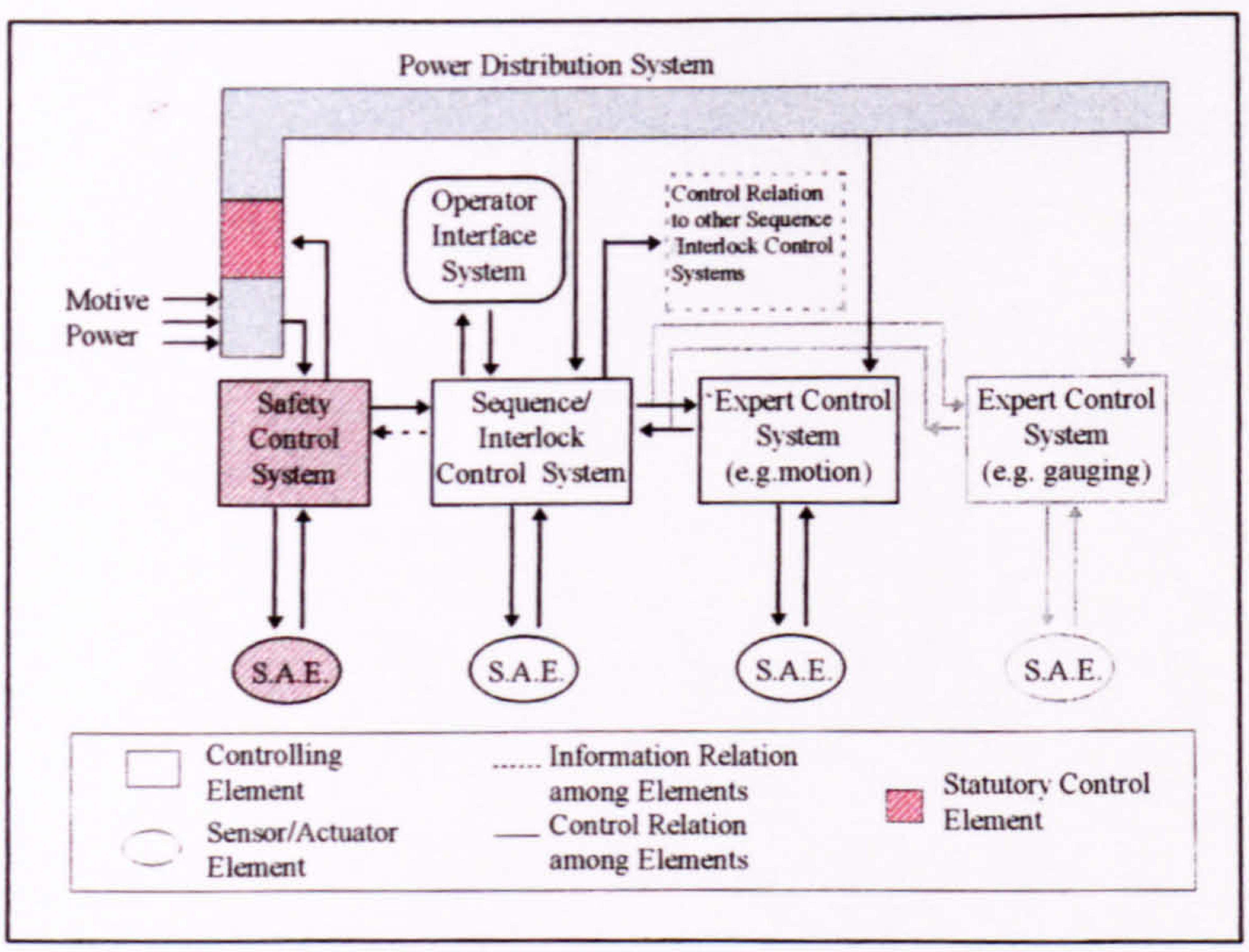
Level 3 - IntraPlant Operations: comprising of IntraArea co-ordination, plant scheduling, maintenance and configuration management, order processing, product quality control: state space size ~ 100*100*100 elements.

Level 4 - Enterprise-Wide Operations: comprising IntraPlant operations involving order processing, logistics, multi plant production scheduling, and inventory management; state space size ~ 1000*1000*1000 elements.

The system model separates logical physical process management policy into four abstract layers, including process regulation, process optimisation, process adaptation, and process organisation. All four layers are present in some form at each level of the automation hierarchy, and are supported by a set of services that provide for the supervision of process behaviour. Taken together these services provide for the "intelligent automation" of industrial processes. The review of architectures within this thesis primarily focuses on level 0 and level 1.

Previous research into level 0 and level 1 systems primarily focus on controlling elements and the communication technology connecting them, [Dilts 1991]. Unfortunately practical applications have a number of other elements that are of equal importance in terms of system function and are themselves subject to a similar evolutionary development. To illustrate this point Figure 3-11 identifies the major elements of a shopfloor control system. The normal sequence/interlock controller and sensor actuator elements are present, however in the model below the power component and *expert* controller are added. The *expert* controller will normally contain its own processing capability. In an Automotive application may be, for example, an NC motion or gauging controller. The SAE are generally binary devices e.g. end stop actuators or fluidic valve devices. The evolution model is further complicated by statutory control elements[19] whose development is constrained by different statutory requirements in different regions.

Figure 3-11 Shop Floor Control Model

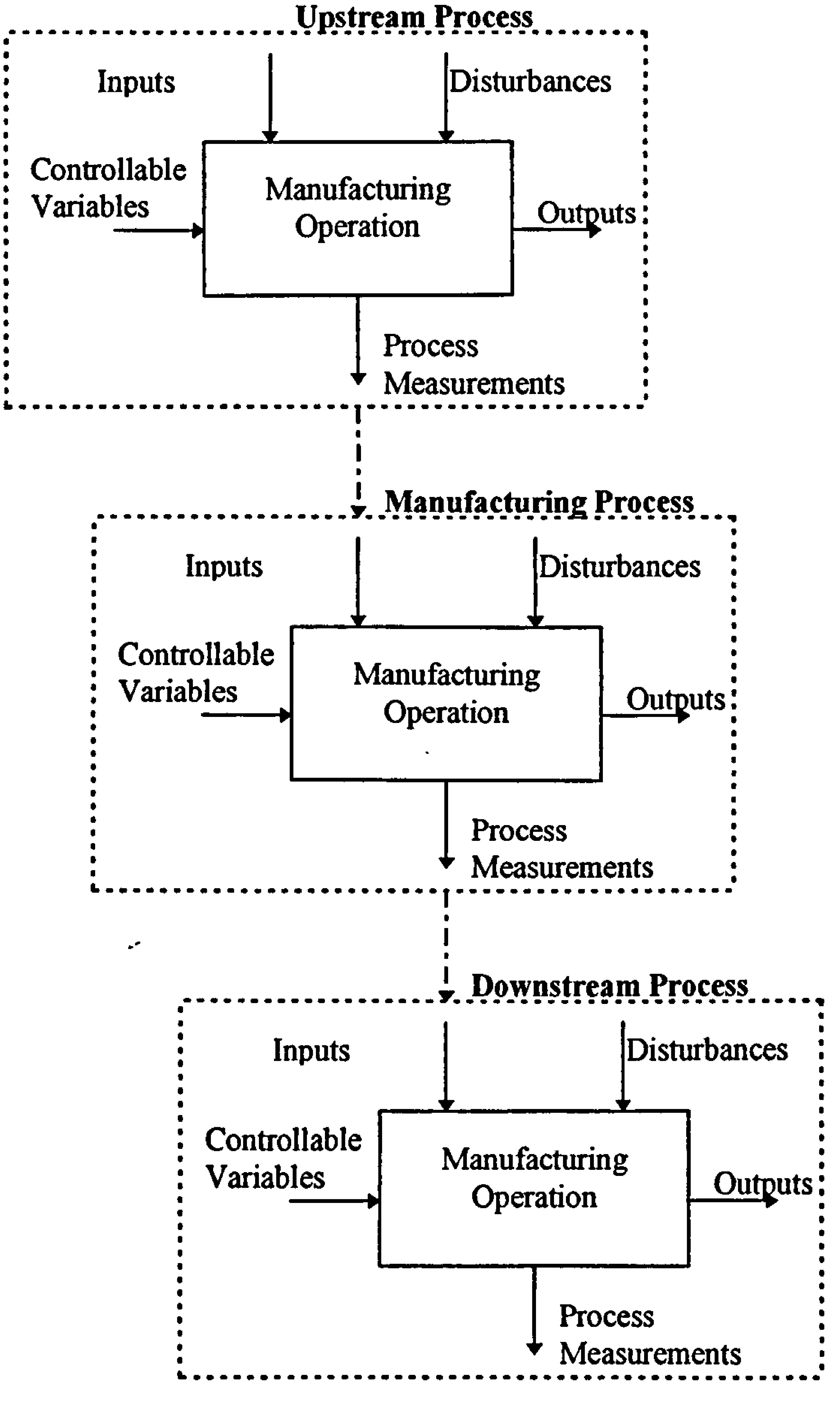


Complex high volume manufacturing is typically decomposed into a series of component processing activities which are further simplified by segmentation into individual

[19] Statutory control elements - Elements ensuring the safety of persons operating the equipment.

manufacturing operations (drilling, grinding, welding etc.). Furness describe a generic model of the individual processes as members of a larger system, [Furness 1996].

Figure 3-12 Diagram of Manufacturing Processes as elements of a Production System.



This model can be used to represent manufacturing operations in the majority of Automotive manufacturing facilities.

3.5 A Case for Adopting a New Approach

The Automotive industry was instrumental in the development of the first programmable logic controllers. The early PLC's reflected this influence by providing a careful match between end user skills, technical requirements and product design. The automotive industry has remained a significant end user of manufacturing control technology; so why has a gap formed between contemporary automotive manufacturing requirements and available technology? The author's research identifies a number of factors, namely:

1. The market for PLC's has expanded rapidly in the last thirty years and hence diffused the ability of the automotive industry to influence design.
2. Automotive strategy in North America and Europe has been changing rapidly in an attempt to compete with the Japanese Automotive Industry. The 1980's produced a strategy that tried to beat the Japanese with increasing levels of complex manufacturing technology. The change to *lean production* methods is a relatively recent change leaving the control technology providers with products designed for a now outdated *mass production* strategy.
3. Contemporary products have been designed with disproportionate influence of technical staff and engineers, which has resulted in the neglect of social and organisational issues. A *lean*' manufacturing environment requires a balanced *symbiotic* design approach.
4. Regional differences in the techniques used to fulfil operational requirements have made it difficult for control technology providers to focus on a particular set of requirements. In North America the most influential initiative in the Automotive Industry has been the OMAC initiative. This has generated strong interest in *Open* P.C. based control solutions, whilst in Europe and Japan a more pragmatic approach has been taken. Europe has led the development and use of Industrial control networks in the automotive industry. Based on the author's industrial experience, in North America industrial control networks are often (mistakenly) linked to the use of *open* P.C. based solutions. In Japan and the Far East a relatively conservative approach to control technology exists. Machines (and hence control systems) tend to be relatively simple with a high focus on cost, size and functionality. The gap between control technology and end user requirements is not so evident in Japan due to the high skill level found in their manufacturing facility. This diversity of requirements further dilutes the influence that the automotive industry can exercise over new product design.

5. The gap between end user capabilities and control technology has to a large extent been masked by increasing levels of support provided. The cost of the support has been hidden in the price of the product. It is common in the automotive industry for seven year warranty and permanent on site support.

The conclusions drawn from Chapter 2 identify that the design and implementation of machine control systems should be closely aligned and play a key role in the enhancement of manufacturing strategy, including life cycle cost, work practices and product/production agility. The supply of technology and technological innovation into the factory environment is a subject of great debate with many reported problems of poor implementation of technological systems and difficult relationships between users and their suppliers.

Many social scientists claim that the one sided interest of engineers in technical aspects, results in the neglect of social and organisational issues and therefore leads to the creation and implementation of inadequately functioning systems [Zairi 1998]. During the past 40 years individual researchers and research groups have repeatedly recognised the existence of this problem and have tried to design production systems that were labelled human centred or socio-technical, [Badham 1995], [Bender 1995], [Emery 1959]. Bender, Haan and Bennett argue that *symbiotic* techniques are required thereby stressing the necessity for co-operation between technical and social elements in designing production systems. This new term stresses that neither technical nor social issues dominate.

Many of the problems raised concerning contemporary systems demonstrate that whilst the social and organisational techniques used on the shopfloor have changed extensively in the past few years; manufacturing control systems and the associated programming languages have remained fundamentally the same. This lack of a complete and consistent environment leads to integration problems that are often detected late in the design life cycle. The design of such complex and heterogeneous systems requires a methodical approach to requirements definition, specification and design as well as verification and validation of the results.

The author proposes that the design of next generation manufacturing control systems[20], require the combination of expertise from a number of different domains. Contemporary methods and tools have the potential to support elements of the manufacturing strategy; however a new design approach is required is required that takes into account the view of technical, human and operational aspects of the problem to fulfil the requirements of this new *lean* manufacturing environment.

3.6 Summary

This chapter has focused on the role of current manufacturing control system hardware and application software with respect to their effect on control system design and application.

The review in this chapter has highlighted a number of key issues, namely:

- Improvements in enterprise integration and the ability to react to foreseen and unforeseen product changes will require the link between control system hardware and application software manufacturer to be broken.
- A life cycle approach is required at all stages that takes into account technical, human and operational aspects of the problem.
- Currently increased performance is often used to increase system complexity rather than providing improvement of system behaviour.
- Considerable difficulties are faced by existing PLC system suppliers due to competitive pressures, loss of key (profit making) segments of their market, and the introduction of working practices in the Automotive industry that do not *fit* with the design of their products.
- Unlike the PLC, current PC based architectures were not originally designed for operation on the shopfloor. This has in some applications led to their failure to meet expectations in the following areas: reliability, modularity, cost, and training.
- IEC1131/3 has resulted in the standardisation of a collection of outdated languages. Whilst some benefit is gained from this language standardisation the languages themselves fail to match with emerging user requirements (e.g. available skills and operating practices).
- Some potentially innovative programming languages have failed in the past due to:

[20] Control System in this context includes sequential control hardware and software, open-loop and closed loop control, power supply systems and sensor and actuator components

1. strong links with particular control or machine tool suppliers leading to competitor reluctance to use the product.
2. Product development in isolation from one or more of the key user groups.

Regardless of the widely differing opinions as to which of the currently available technologies is best suited to a particular application, there is broad agreement amongst managers, engineers and operational staff that taking advantage of the latest manufacturing technologies plays a key role in ensuring the success of an enterprise in today's fiercely competitive global market. A requirement has therefore arisen to seek ways and means of enabling the design and construction of a new generation of manufacturing control systems in order to more effectively meet with the changing needs of this new manufacturing environment.

This chapter has substantiated the first part of the author's hypothesis that the design and implementation of contemporary manufacturing control systems is inappropriate when viewed from a business context. The following chapters will identify a design framework able to create a more appropriate next generation of control system.

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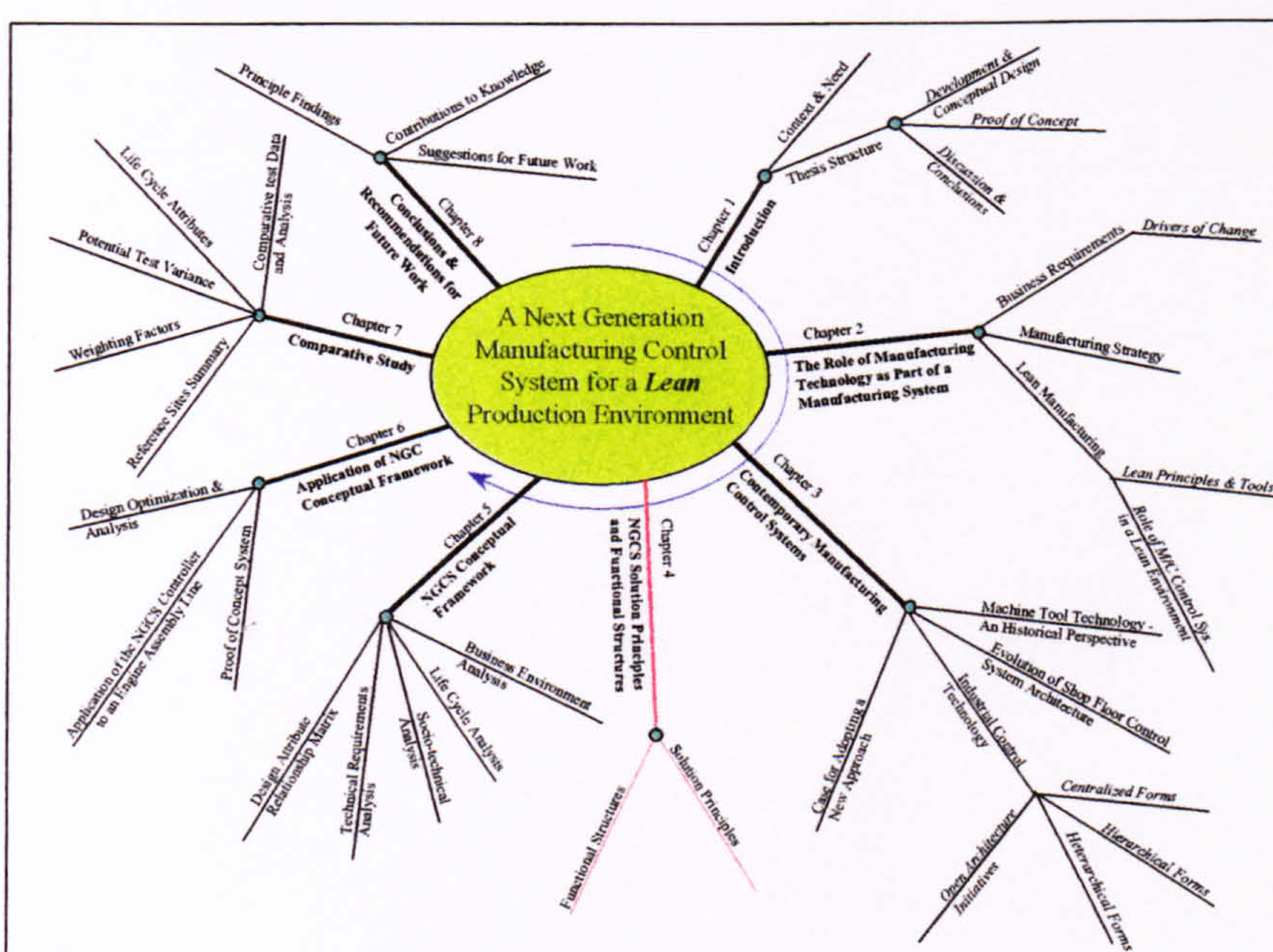
CHAPTER 4

NGCS SOLUTION PRINCIPLES AND FUNCTIONAL STRUCTURES



4. NGCS Solution Principles and Functional Structures

4.1 Introduction

This chapter will identify through abstraction, the primary *Solution Principles* and *Functional Structures* that will underpin a design framework that facilitates and guides the design of Next Generation Control Systems used in the automotive industry. The chapter is divided into two sections: The first section identifies *Solution Principles* required of the Design Framework. In the course of identifying these principles, work from which the author has drawn elements of framework definition are introduced. The second part of the chapter identifies *Functional Structures* that represent the principle design and analysis environments. Supporting tools and methods are introduced to facilitate the management of complexity and facilitate modular, stable designs with inherent structural stability.

4.2 Solution Principles

4.2.1 Use of a Prescriptive Framework Model

Engineering Design can be defined as the systematic, intelligent generation and evaluation of specifications for artefacts whose form and function achieve stated objectives and satisfy specified constraints. [Dym 1999]. Design is a creative process however tools and techniques can be used to support and structure this creativity.

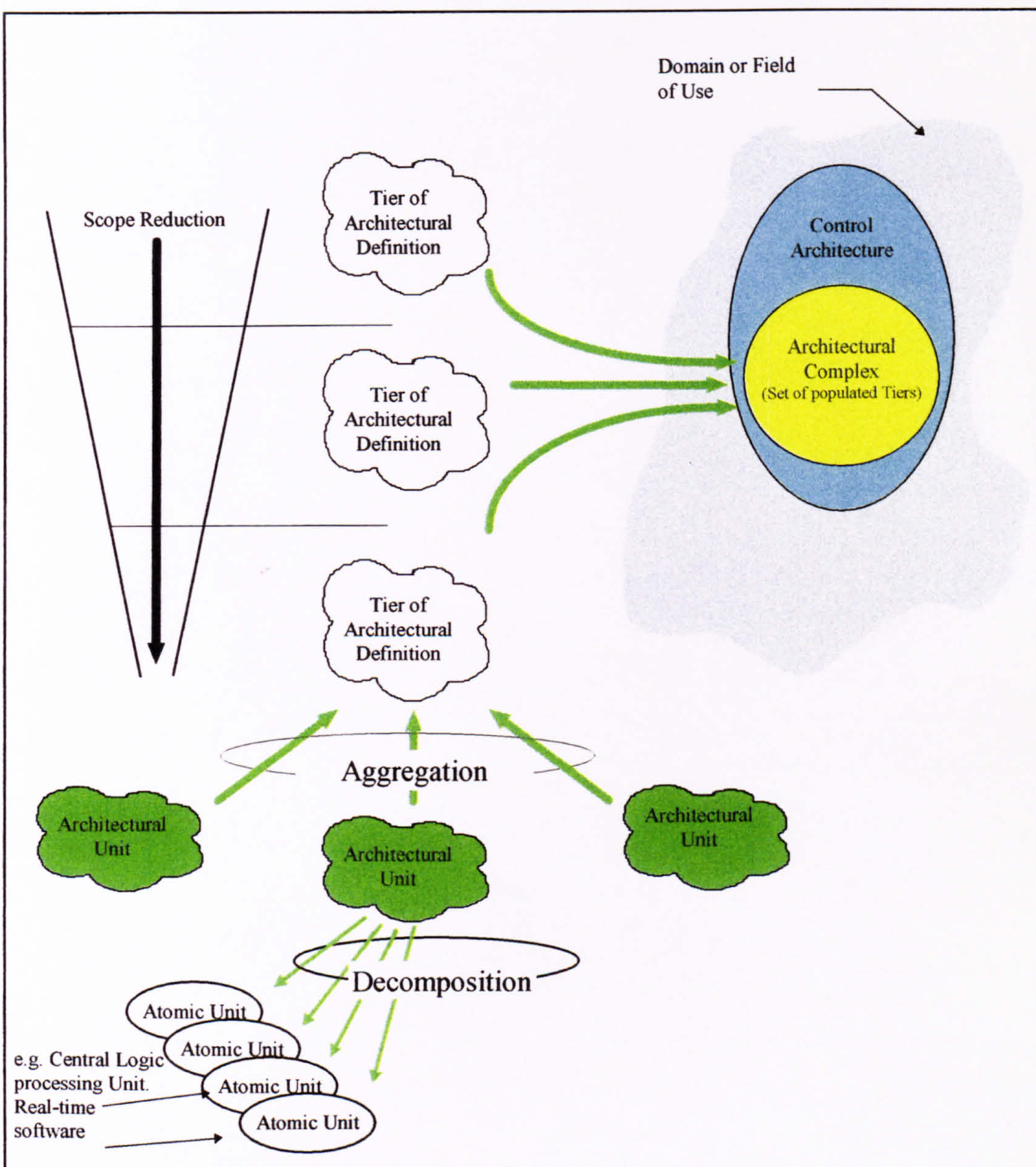
The majority of design frameworks fall into one of two categories; namely descriptive frameworks or prescriptive frameworks, [Cross 1989]. Descriptive frameworks emphasise the importance of generating a solution early in the process and then subjecting that solution conjecture to detailed analysis and evaluation. Of course the analysis and evaluation may reveal fundamental flaws in the initial conjecture causing the design to be abandoned, and a new concept generated. The process is heuristic using previous experience, general guidelines and rules of thumb. *The conceptual framework described in this chapter adopts the second category of design framework, namely a prescriptive model.* This category of frameworks are concerned with detailing a more systematic procedure and are often regarded as providing a particular design methodology.

4.2.2 Standardized Terminology and Structures

Senehi and Kramer propose common terminology for discussing architectures and a common framework for organising information about control architectures, [Senehi 1998]. Their conceptual framework is based upon developing a number of *tiers* of architectural definition.

An instance of the framework with a set of populated tiers is termed an *architectural complex*. Each tier is made up of a number of *architectural units*. These in turn are an aggregation of the fundamental building blocks of their structure, namely *atomic units*. An *atomic unit* is defined as the lowest level of decomposition of a functional module or unit, for a particular architectural definition. In addition, the tiers are designed to ensure decisions made at lower tiers are consistent with those made at higher ones. Hence an implementation must conform to the specifications of the given tier and all higher tiers of the architecture complex. Both concepts are illustrated in Figure 4-1.

Figure 4-1 Elements of an Architectural Complex. (Derived from Senehi & Kramer.)



Two additional concepts are proposed to complete the definition of tiers; *relations* and *partial orderings*. A relation defines an association between architectural units. Using these relations, it is possible to generate partial orderings of an architectural complex that may be used to group architectural units into tiers.

A number of different types of relations can be defined. The most applicable in hierarchical control systems is decomposition/aggregation. Decomposition/aggregation relates an item to its parts. For example, a manufacturing facility is an aggregation of individual machine tools and hence each machine tool is part of the decomposition. Any architectural unit that is not atomic is an aggregation.

Many relations can be used to define a partial ordering for the *tiers* in an architectural complex. In a partial ordering of a set, any two arbitrary set elements that are related can have a sense of direction established. If 'A' and 'B' are architectural units, for decomposition/aggregation relations A< B meaning A decomposes into B. This may be used to order the different elements of the machine tool control system within a facility.

In addition to organising information about control architectures, Senehi and Kramer identify the need for *elements of architectural definition*. The elements are conceptual entities, which may or may not have any physical realisation (i.e. hardware software).These are:

1. statement of scope and purpose,
2. domain analysis,
3. architectural specification,
4. methodology for architectural development,
5. conformance criteria.

Statement of Scope :- The statement of scope identifies:

- the situations or domain to which the tier is intended to be applied,
- general characteristics identified which set limits to its applicability to other domains,
- functions that are out of the scope of the tier.

Statement of Purpose :- The statement of purpose identifies the objectives of the tier within the given scope. Within this statement the major objectives of the tier need to be outlined, for example for the next generation controller, 'functionality designed to operate in a multi-skilled working environment' may be an objective for one of the high level tiers with a wide scope.

Domain Analysis :- Domain analysis is required before an architecture can be formulated. The author cites the failure of this step as one of the most significant reasons why current shopfloor control systems are failing to meet automotive end-user requirements. Within the context of this thesis the background material that determines the characteristics of an automotive domain is established in Chapters 3 and 4. Different views require different forms of domain analysis. The types of analysis that are significant for a next generation shopfloor control system are: functional analysis, information analysis and operational analysis.

- *functional analysis* is concerned with all functions within the scope of the architecture that a conforming control system must be able to perform and the sequence and dependencies of the functions,
- *information analysis* takes into account information external to each atomic unit needed for a conforming control system to function properly,
- *operational analysis* is concerned with functions and information in the domain that is influenced by operational or social requirements. This emphasis stresses the necessity for co-operation between technical and operational elements in defining the framework.

Architectural Specification :- The Architectural Specification is a prescription for the architectural units; how they are connected and how they interact. The composition of any architectural units that are not 'atomic' should be specified.

Methodology for Architectural Development :- Senehi and Kramer identify a 'set of procedures for refining and implementing an architecture' as a *'methodology for architectural development'*. For example a methodology for producing an architectural specification at one of the lower tiers may include the following:

- set machine actuator limits (e.g. maximum number of actuator devices),
- set functional limits (e.g. maximum two servo axis, no interpolation),
- complete timing analysis (maximum scan time).

Conformance Criteria :- .Conformance criteria are standards that specify how an architectural unit at one tier of an architectural complex conforms to the architectural specifications of a higher tier. A *conformance test* is a procedure that determines if the *conformance criteria* have been met. These terms allow the definition of *conformance classes* of an architectural complex which identify sets of different and incompatible choices of architectural features. The advantage of defining conformance classes for a shop floor control system is to have choices within the architecture, while allowing the bulk of the architecture to remain unchanged. This will allow architectures for specific *classes* of machine control system to coexist as variants of the same basic architecture.

In giving the *tiers* a sense of order Senehi and Kramer prescribe a *top down* approach so that decisions made at lower tiers are consistent with decisions at higher ones. The use of an iterative decision making process where a *top down* and *bottom up* approach is followed will maintain the needs of both upper and lower *tier* requirements ensuring that lower tiers of architectural definition are not constrained needlessly by upper *tier* decisions.

From Senehi and Kramers work the author identifies the need for the NGCS Framework *to adopt a standardised terminology that allows he discussion and development of a clear set of criteria* as a *Solution Principle.*

4.2.3 Use of Views Analysis and Structured Scope Management

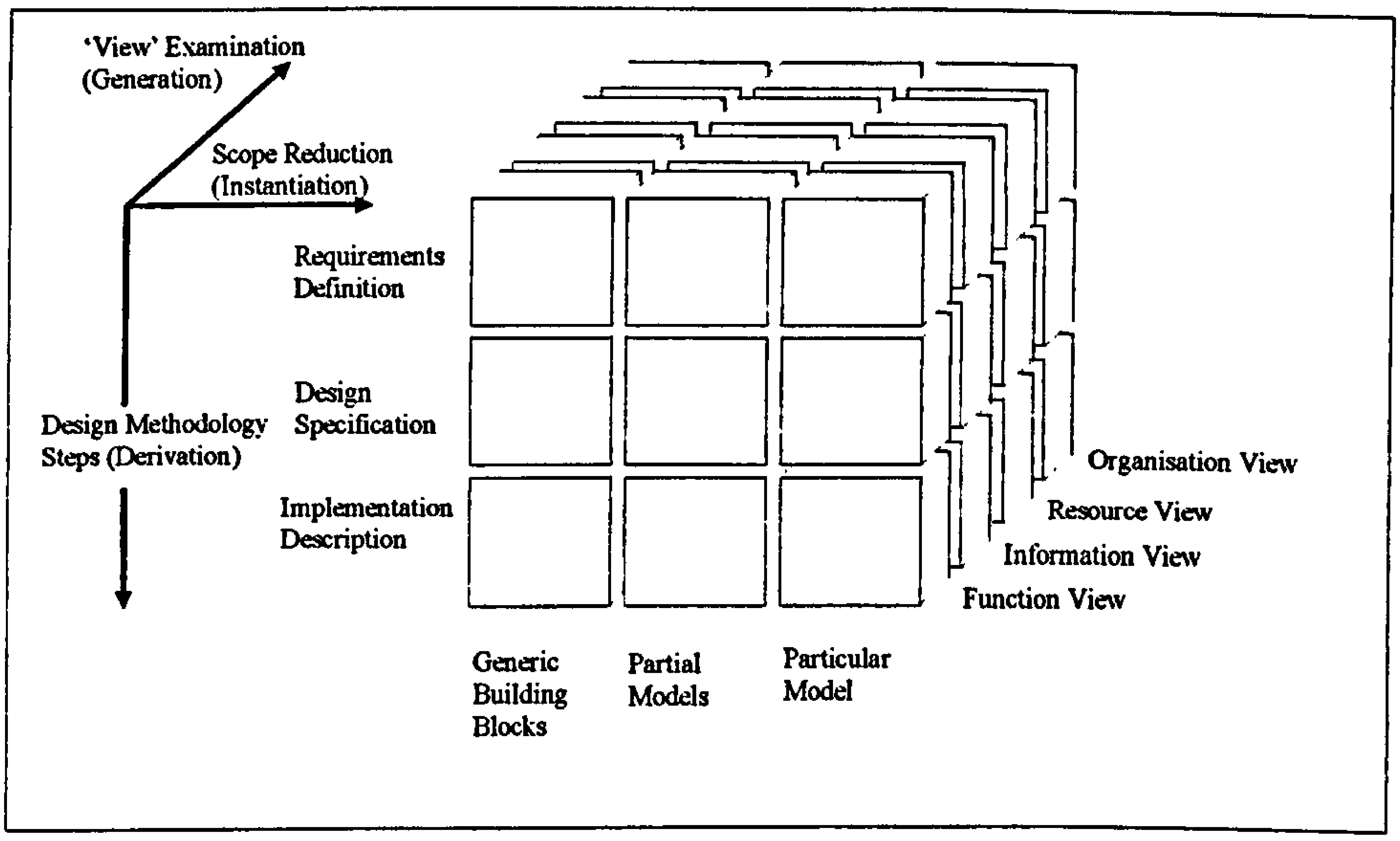
One of the most widely researched design frameworks in this field is the Open System Architecture for CIM[21] (CIMOSA) and the associated methodology proposed by the ESPRIT consortium AMICE[22]. The CIMOSA project was initiated in the mid 1980's and with extensions took some ten years to complete, [AMICE 1993]. The aim of the project was to develop: (i) a generic CIM reference architecture for the creation and execution of enterprise models, i.e. a modelling framework, [Panse1990] and (ii) a set of rules for building CIM systems based on the architecture, i.e. an integrating structure, [Klittich 1990].

CIMOSA provides a system life cycle framework which takes into account, initial conception, design, implementation, maintenance, operation and reuse. This guides designers through the development and implementation of CIM systems and system components, that can be added and removed at will. The life cycle starts with the collection of business requirements via a domain analysis. These are then fed into a requirements definition model, which in turn are

[21] CIM -Computers in Manufacturing.
[22] AMICE: European Computer Integrated Manufacturing Architecture

translated into a design model and a comprehensive description of the implemented system. Finally the model is released for operation to control and monitor factory systems.

Figure 4-2 CIMOSA Modelling Framework, [AMICE 1993].



The CIMOSA cube is illustrated in Figure 4-2. The cubes three-dimensional framework has a dimension of genericity, a dimension of enterprise models and a dimension of views. The author has adapted this terminology to better suit the architectural requirements of a design framework for Next Generation shop floor control systems, namely:

- the dimension of '*scope reduction*' (instantiation) progresses from generic building blocks to greater levels of specificity, until a model for a particular operational domain has been identified. A structured reduction of scope will aid the design of *architectural units* that can be used in a number of *tiers* and hence have a wide range of application,
- the *design methodology steps* (derivation) provides the design and development steps required. Starting with statements of requirements the process must advance through a structured design process that concludes with a description of the system implementation.,
- the dimension of views offers the possibility to work with sub-modules, focusing on different aspects of the enterprise. An example representing a function view is noticeable in the 'proper and modified hierarchical forms' presented in the previous chapter. In this example additional hardware is used (potentially increasing the hardware failure rate) to obtain machine/control modularity and simplicity.

CIMOSA is a descriptive framework that does not prescribe methods to design a system, [Zwegers 1998]. Hence applying CIMOSA does not result in operational systems, let alone systems able to function efficiently in a *lean* production environment. Given that it does not offer guidelines and reference models that support designers in the transition from requirements to practical specification, the value of CIMOSA should be seen as an overall framework within which enterprise integration is described.

The author concludes that the views proposed by CIMOSA give a valuable insight into particular aspects of the system and is therefore adopted as a Solution Principle, however the complex array of organisational, technical and human requirements evident in lean systems, requires an additional feature that allows their simultaneous examination to ensure overall optimisation. The second principle derived from CIMOSA is the need for structured scope management that facilitates modular, stable designs with inherent structural stability.

4.2.4 Need for a Business Environment Analysis

There is evidence that for a design framework to achieve relevance and be adopted it must be specific to a particular industry's needs and constraints as determined by culture, market, products and technologies, [Clark 1993]. This points to the *need for a strong element of business environment analysis leading to an essential understanding of how design outcomes will interact with company organisation, its culture and environment.*

4.2.5 A Sociotechnical Approach to Design

Research that stresses the necessity of co-operation between technology, organisation and people is normally labelled *sociotechnical*, [Emery 1959], [Mumford 1983], [Taylor 1993], *human centred*, [Badham 1995] or *anthropocentric*, [Wobbe 1992]. Throughout this thesis the term *sociotechnical* is used to define a manufacturing control system in which the interdependent nature of technology and organisation is given a high priority.

Research and development of symbiotic systems has concentrated mainly on the design of man machine interfaces, ergonomic requirements and the consequences for worker skills and learning, [Benders 1995]. Whereas most contemporary research in this area concentrates on manufacturing applications [Zarakovsky 1991], information systems in general [Blacker 1988] and knowledge base systems [Kirby 1992] have also been addressed.

The Sociotechnical Systems (STS) paradigm is a design approach that promotes the notion that organisational systems function effectively and proactively because the elements are compatible and integrated with each other, and therefore no one element can be taken alone and modified without affecting other elements. The presence of these interdependencies requires that the STS design methodology be addressed early in the design process. *Duimering et al.* go further by suggesting that it is more productive to redesign the organisational structure before implementing available technology than to hope technology will bring about manufacturing effectiveness, [Duimering 1993].

Scandinavia has fulfilled a prominent role in sociotechnical research within Europe with the UTOPIA project, [Bodker 1987]. Volvo's Uddevalla plant gained world-wide attention with its unique symbiotic organisational design, [Bennett 1992]. The result was a vehicle assembly plant with six product shops centred in groups of three around two inspection shops where the cars were tested. Every product shop contained eight teams, each team assembling a complete vehicle in two hour cycles. Although Volvo's work in this area has been largely phased out, renewed interest has emerged with several initiatives sponsored by the European Commission for example the ESPRIT and FAST programmes. Other related concepts such as Total Quality Management, [Lawler 1992], the Japanese *kaizen* perspective [Imai 1986], [Lillrank 1989] and Reliability-centred Maintenance, [Moubray 1997] have also played a part in promoting a more balanced view of technology design and implementation. In Germany the search for more flexible production systems has led to extensive organisational experiments, with programmes like Arbeit and Technik, [Latnik 1995].

Despite the large body of research completed in this area the application of STS principles has been confined to a relatively small number of organisations, [Majchrzak 1995]. Majchrzak and Finley conclude that the limited diffusion of the STS approach can be attributed to three main factors:

1. the inherent complexity when technical, human and organisational factors need to be combined to produce a production system.
2. the high number of variables that need to be simultaneously considered in the design of a sociotechnical design. (Majchrzak and Finley identify in excess of three hundred variables).
3. the additional complexity induced by the large number of relationships that are discernible between the variables.

Their research attempts to manage this complexity by: constructing a knowledge base with a comprehensive list of variables and relationships among the variables, manipulating the knowledge base to make sociotechnical decisions, and applying the decisions to the architectural complex design. Majchrzak and Finley use five knowledge sources to construct a comprehensive knowledge base of STS variables and relationships, namely [Majchrzak 1995]:

- industry standards and contemporary manufacturing concepts,
- theoretical and anecdotal literature to identify propositions,
- empirical studies on the implementation of manufacturing technology,
- consensus building meetings with industrialists in which each specific relationship is discussed,
- site visits utilising standardised interview and observation protocol.

Majchrzak and Finley's knowledge base consists first of a comprehensive list of operational features describing a sociotechnic work system made up of 17 categories. Examples include:

Business Objectives, Employee values, Skills, Production and Process Characteristics. The categories are broken down further, into more than 300 different variables.

Hypothetically, the knowledge base could contain a number of ideal relationships among each of the system variables. Given that some of the processes contain a large number of variables, the number of ideal relationships among each may be significant. Practical constraints will restrict the design making many of the ideal relationships impracticable. To assist the designer with these *trade offs* a method of experimenting with alternative design features to determine those that have the greatest potential for increasing organisational effectiveness is required. Majchrzak and Finley term this feature a *sensitivity analysis model.*

Traditional approaches to technology implementation are characterised by two fundamental weaknesses. First, *technology-centred* approaches neglect human and organisational factors in the design and implementation process resulting in the widespread experience of failed technology projects that often over-run their original timing and budget, [Majchrzak 1991]. Secondly many of the economic and social benefits of new technology result from post-adoption configuration of the system to fit the particular technical and organisational context of the user organisation, [Badham 1995]. The author adopts as a *Solution Principle* the need for *Sociotechnical Analysis and tools as part of the NGCS design framework.*

4.2.6 Solution Principles Summary

A number of issues arise when current design methods are used to design shopfloor control systems for a lean manufacturing environment, namely:

1. The methodologies presented often contain generic concepts. Their generalised nature may be viewed as one of their strengths allowing wide spread use in many different situations and domains; however, the operationalisation of these concepts is a difficult process often leading to misapplication of the architecture.
2. As the design develops, the control system specification moves from generic building blocks to particular units causing an inevitable narrowing of the scope and applicability. This process is often poorly defined, resulting in systems and sub-systems with a narrow scope of applicability.
3. Shopfloor control systems designed to work in a multi-skilled team based environment (typical of a *lean* manufacturing environment) must address a complex combination of process, technical and human requirements. The primary focus of contemporary methods is on the application of manufacturing technology and its relation with the production

equipment. This often leads to specific *views* of the system being missed, ignored or given inappropriate emphasis.

4. Continuous improvement is one of the cornerstones of *lean* manufacturing. The objective of contemporary architectures is to define the *ideal solution.* As a result little attention is paid to processes that monitor and feedback design output performance and address imperfections.

The *Solution Principles* identified in this section of the chapter are summarised below. Their principle aim is to guide the development of *Functional Structures* that provide manufacturing control systems that: correctly relate to business objectives and more effectively contribute to manufacturing competitiveness.

1. The NGCS Framework is best described by a prescriptive design model detailing a systematic design methodology.
2. A strong element of business environment analysis is needed to ensure the design is relevant to the automotive industry.
3. Standardised terminology is required that allows discussion and development of a clear set of criteria.
4. The framework should incorporate structured scope management that facilitates modular, stable designs with inherent structural stability.
5. Standardised *Views* that capture the requirements of a lean manufacturing environment are essential.
6. Finally a Sociotechnical approach to design is required that promotes the notion that organisational systems function effectively and proactively because human and technical elements are compatible and integrated with each other.

4.3 Functional Structures

The work contained in this section outlines the *Functional Structures* that together make up a Design Framework for the production of a Next Generation Control System (NGCS). The NGCS Design Framework consists of four interconnected phases (Figure 4-3), namely: a Design Requirements, Analysis and Capture (DRAC) phase, a Design Implementation phase, an Application and Operation phase and a feedback phase to provide Design Optimisation.

4.3.1 DRAC Phase

The Design Requirements Analysis and Capture phase introduces a body of *methods* which represent the different stages through which the design process must pass. Each *method* is supported by one or more design and development tools (shown in yellow). The first stage of the DRAC is called the Business Environment Analysis phase. The principle aim of this stage is to define the strategic and product priorities of the organisation. The output provides direction in terms of a Manufacturing Strategy, Product definition (in this case an internal combustion engine) and detailed Manufacturing objectives. The second stage is termed the Life Cycle Analysis (LCA). The aim of LCA process is to initiate the dimensional and process flow planning, identify and prioritise lessons from previous programs, analyse life cycle costing and understand the relationship of the system in terms of reliability and maintainability.

The third analysis method is termed the Sociotechnical Analysis and aims to provide an ordered set of variables with defined relationships. The number and complexity of the variables presented to the design team are very high at this point in the process. It is important that the design team do not attempt to curtail the complexity by reducing the number of variables to a manageable number. This strategy will prematurely judge particular variables to be constrained or eliminated and as such not worthy of design attention.

The STS paradigm states that each variable has some interaction with other variables in the sociotechnical system. These relationships are considered to be as important as the variable itself and given the large number of variables; the number of relationships present an even greater challenge. Compiling these relationships into one place (such as the design team) and accessing the relationships is likely to be a difficult task to carry out manually, therefore it is essential that suitable tools be procured to facilitate this part of the process.

The final phase of the DRAC environment is the Technical Requirements Analysis. The objective of the work at this stage is to use available design methodologies and tools to translate the variables and relationships into a set of NGCS Design Attributes that may then be used to develop an NGCS Reference Architecture and a catalogue of implementation technologies. The objective of the Reference Architecture is to serve as a basis for the Technical Implementation of specific NGCS control systems that encompass all the identified tiers of architectural definition within a specific application area. The implementation catalogue contains appropriate hardware and software technologies that fulfil the design attributes generated as a result of the DRAC process.

The DRAC Phase builds an implicit decision making process, that violating one ideal relationship is less damaging than violating others. The designer must recognise that the inevitable compromises found in practical designs may surface as a flaw in the completed design and hence documentation of the violations applied provides a rationale for the compromises. To assist the designer the decisions made within the DRAC phase are monitored at every stage by a Design Attribute Relationship Matrix (DARM). The objective of the DARM is to oversee the relationship between design decisions and the manufacturing strategy that it supports.

A detailed review of each phase of the DRAC environment is presented in Chapter 5.

4.3.2 Design Implementation Phase

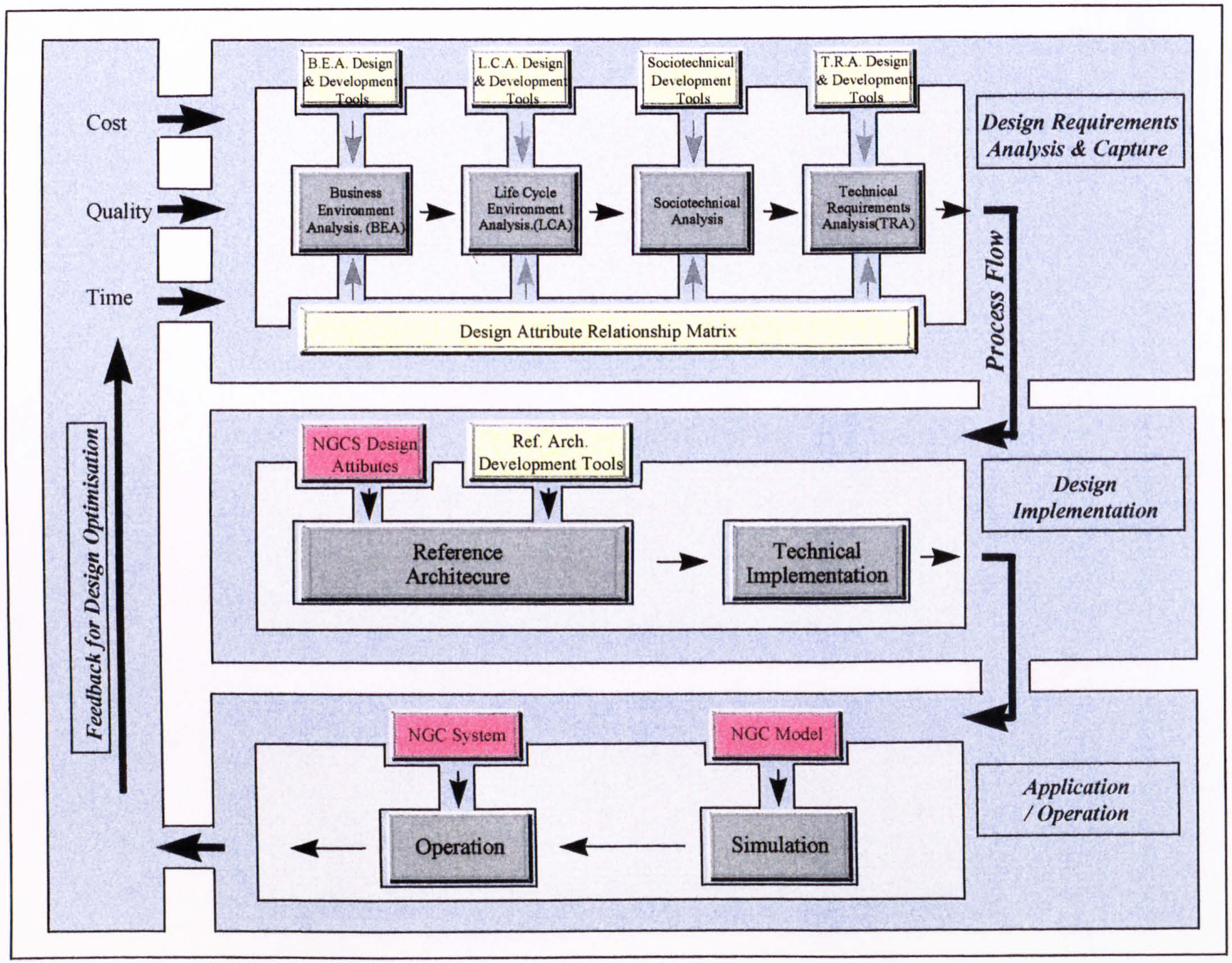
The Design Implementation Phase employs the Reference Architecture and selected technologies to produce an NGCS practical implementation. A *proof of concept* system and practical implementation on a hign volume Automotive Assembly line are presented in Chapter 6.

4.3.3 Design Optimisation Phase

The completion of the implementation phase often signals the end of the design and development process. The study of contemporary applications show that to conclude the development process at this point results in a/ end users living with design flaws on a long term basis or b/ end users providing their own *fixes*. Within the context of this thesis the author categorises the *fixes* applied by the end user into three areas, namely: cost, quality and time. Cost *fixes* may be, for example where additional skilled people are employed to cope with system complexity that cannot be handled by the normal production team. This design flaw manifests itself in the form of software consultants and electronic technicians dedicated to the maintenance of particular parts of the system or production facility. An example of a quality *fix* may be in the form of process variability caused by poorly defined technical requirements or process definition. An example of a time element is the additional period built into product launch and development plans to compensate for excessive training and equipment familiarisation. Time penalties also surface during the operational and reuse phases in the form of change over time and equipment breakdown during production time.

The NGCS Design Optimisation phase recognises the existence of these design flaws and seeks to adjust the design to eliminate or minimise their use. The adjustments may be to the operating environment or the technical design. Following each iteration of the design the *Design Optimisation Feedback* must be reassessed. This may be achieved by analysis, simulation or practical tests.

Figure 4-3 Next Generation Control System Design Framework



4.4 Summary

This chapter presents an overview of development architectures and frameworks applicable to the development of manufacturing control systems. Their role as an essential tool to assist in the understanding of manufacturing control systems is discussed. The sources from which elements of the new framework are drawn, are highlighted and additional concepts considered necessary by the author identified.

An overview of the NGCS Design Framework is presented. Four distinct phases are identified namely: Business Environment Analysis, Lifecycle Analysis, Sociotechnical Analysis and finally the Technical Requirements Analysis. The four phases are bound together using a mapping process in the form of a Design Attribute Relationship Matrix (DARM).

Chapter 5 will expand the understanding of the framework by developing the solution principles and functional structures (Figure 4-3) outlined in this chapter. Each phase of the Framework will be described in detail and where possible the interconnections between each phase formalised.

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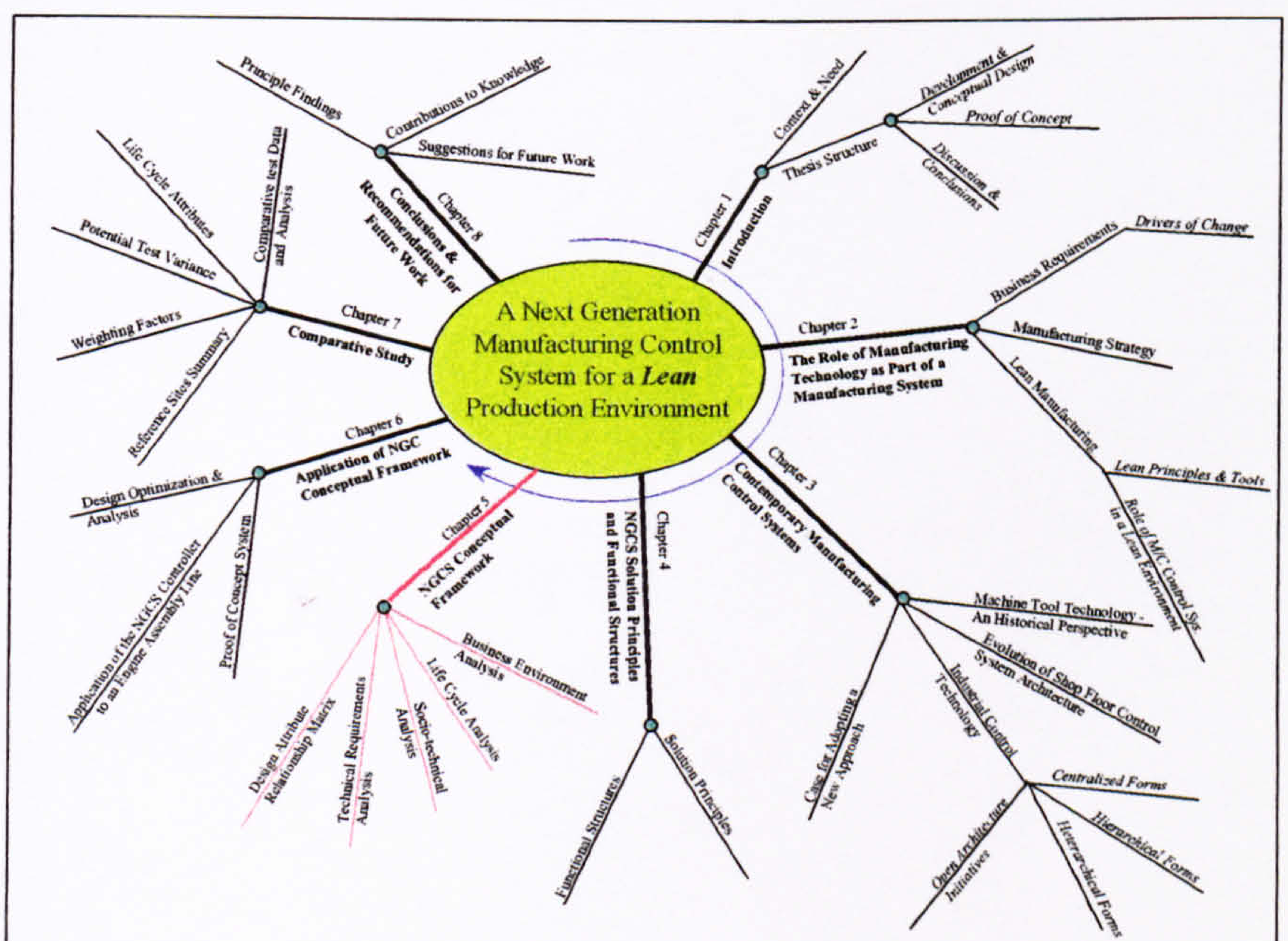
CHAPTER 5

NGCS CONCEPTUAL FRAMEWORK



5. NGCS Conceptual Framework

5.1 Introduction

The creation of a new automated manufacturing line is based on the use of numerous procedures, methods, tools and checklists established over many years. One part of the activity relates to design and implementation of the control system. The ad-hoc nature of the current approach means that there is little visibility of the interconnections between the business, sociotechnical and technical aspects of the control system specification and design process. As a result of this it is difficult to map business objectives through the design process to ensure they appropriately impact on the implementation of the control system. Chapter 3 identifies that this failure often leads to the creation of control systems that are inappropriate when viewed from a modern business context.

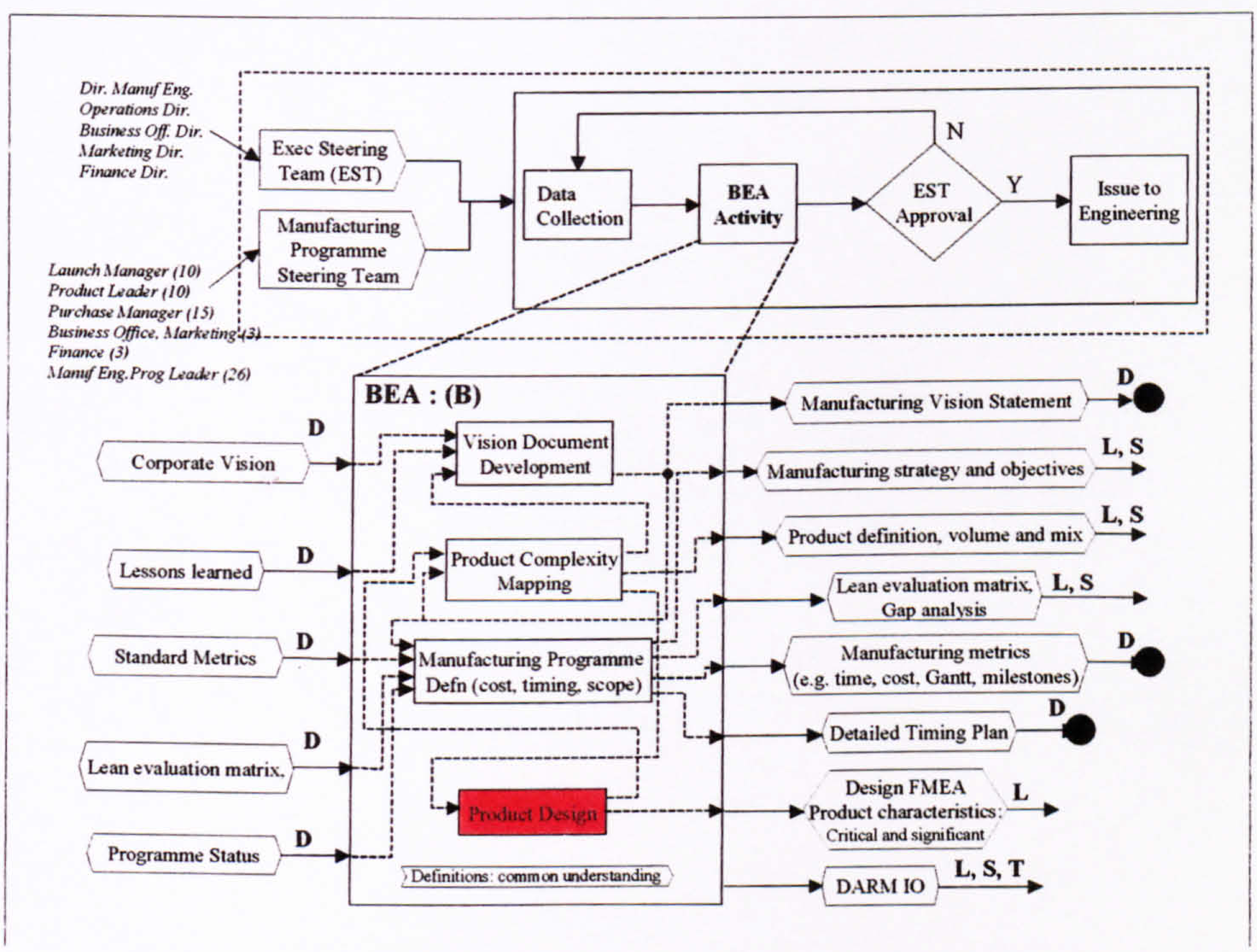
In this chapter the author has taken the solution principles and functional structures (Figure 4-3) outlined in Chapter 4 and modelled the behaviour of each element in the control system design process in the form of a prescriptive model. Where possible the interconnections between each phase have been formalised.

The mapping process is summarised in the form of a Design Attribute Relationship Matrix (DARM), which highlights to the various stakeholders in the design process: a/ the relationship between the key business, lifecycle, socio-technical and technical design factors and, b/ promotes a method of forward and backward propagation between them.

5.2 Business Environment Analysis

The first stage of the Design Requirements and Capture (DRAC) phase is the Business Environment Analysis, (Figure 5-1). The aim of the BEA is to collect Product and Corporate requirements and provide strategic direction for the manufacturing team working on the next generation controller. The human resources required are an Executive Steering Team (EST) made up of senior management from the organisation, Manufacturing Program Steering Team (M-PST) and Program Management group. Figure 5-1 identifies the four principle activities contained within the BEA activity, namely Vision Document Development, Product Complexity Mapping, Manufacturing Programme Strategy Definition and Product Design. The interface to Product Design is discussed however the design process itself is considered by the author to be outside the scope of this work.

Figure 5-1 Business Environment Analysis

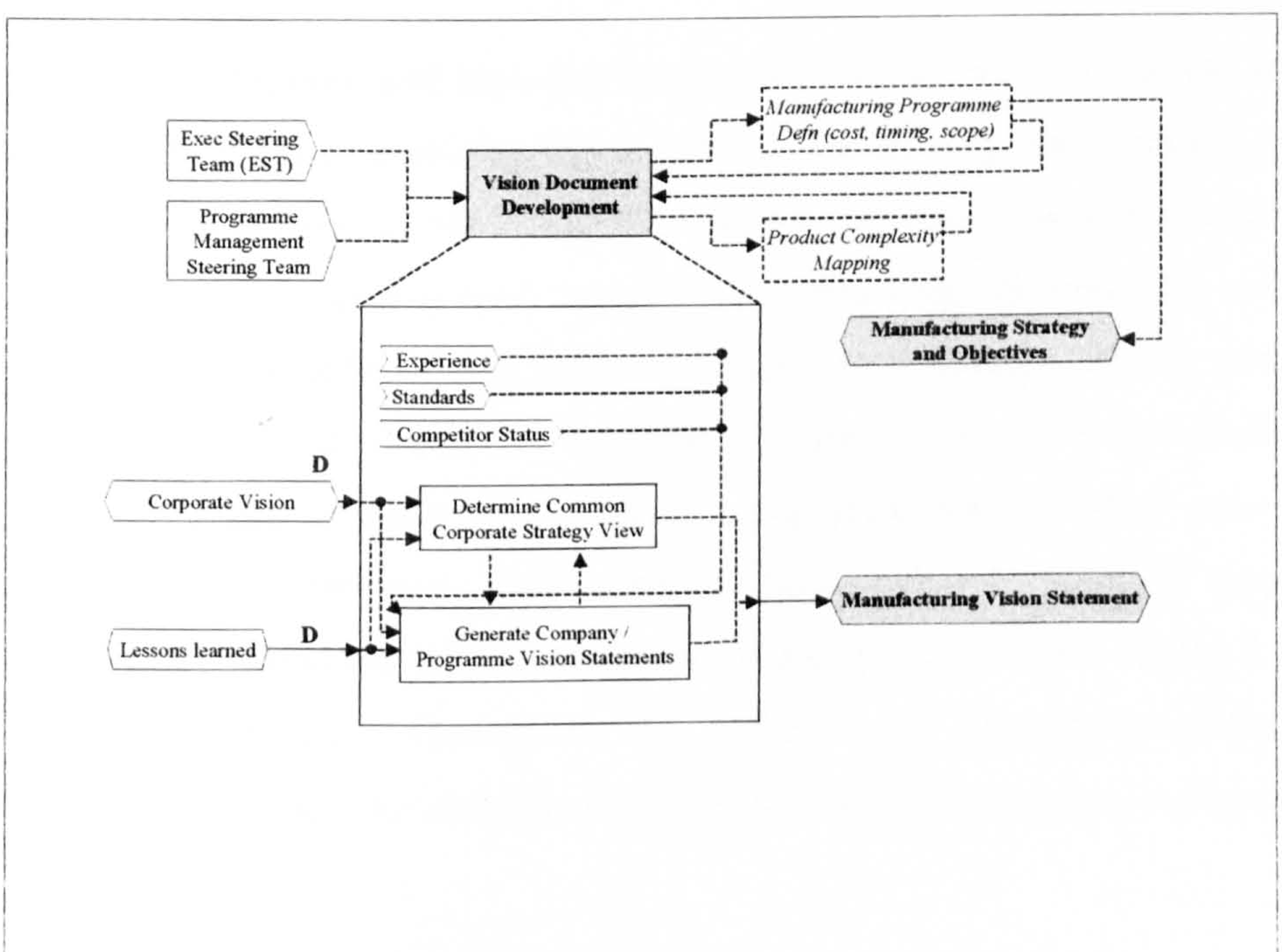


5.2.1 Vision Activity Development

The Vision Document Development activity requires the active involvement of the EST and M-PST teams. The primary input documents are the Corporate Vision Statement and high level lessons learnt. Further to this, it is expected that members of the EST and M-PST are able to provide experience of the business environment, an awareness of current/future legislation and knowledge of competitor status.

During the activity the two groups work to determine a common corporate strategy view and generate a program vision statement. The Vision Document Development activity provides direction to two other activities within the BEA: the Manufacturing Programme Definition and Product Complexity Mapping.

Figure 5-2 Vision Development Process



5.2.2 Product Complexity Mapping

The aim of the Product Complexity Mapping activity illustrated in Figure 5-3, is to ensure appropriate levels of flexibility and agility are built into the manufacturing facility to facilitate the production of the end product (in this case an Internal Combustion Engine). This will in turn influence the design of the associated manufacturing control system. The Management of complexity is also a key aim of the activity to ensure cost and operating complexity is controlled. In the case of an internal combustion engine a block diagram is produced to show the principle changes that are made to step from one engine derivative to another. Figure 5-4 shows how from a core engine with a displacement of 2.0L complexity can be minimised by making selective changes to produce 1.8L, 2.3L and 2.8L versions of the same base engine. Additionally core technologies common to all derivatives may be implemented to provider customer requirements. Examples include variable valve timing and turbo charging.

Product Complexity Mapping and management requires the active involvement of the M-PST and the Simultaneous Engineering Team (SET). The activity also requires data input from, and provides feedback to; the Vision Document Development and Product Design activities. A four-stage process is used to construct a document defining the end product definition, volume and complexity mix. The first stage of the internal activity establishes a detailed understanding of the need for complexity from a customer's perspective. The second and third stages evaluate the required complexity for potential rationalisation followed by a study to determine manufacturing feasibility. In addition to providing feedback to activities within the BEA environment it also provides input for the Life Cycle and Socio-technical phases. Throughout the program the complexity status of key components must be tracked. An example of a tracking document is shown in Figure 5-5.

Figure 5-3 Product Complexity Mapping

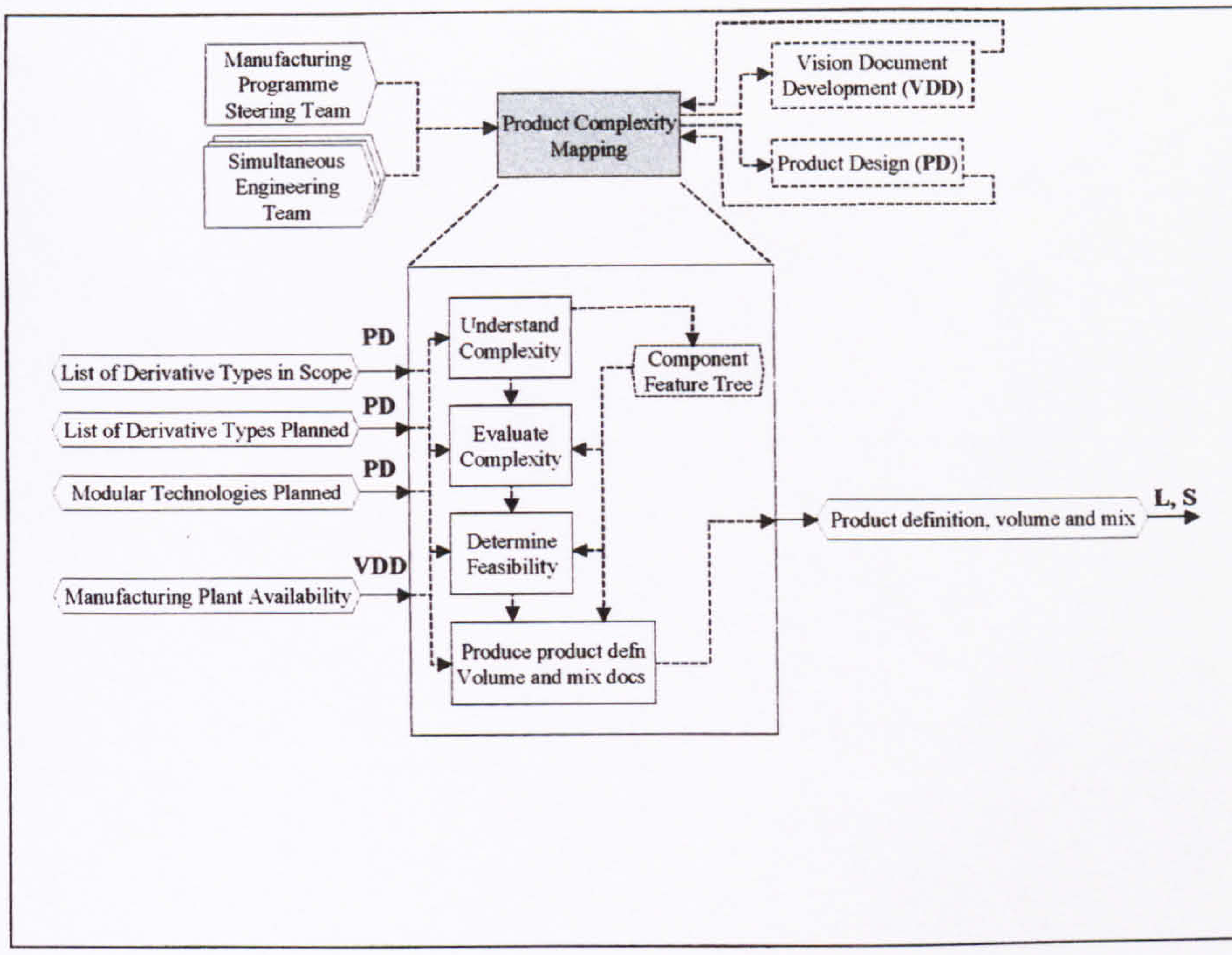


Figure 5-4 Core Engine Complexity Mapping

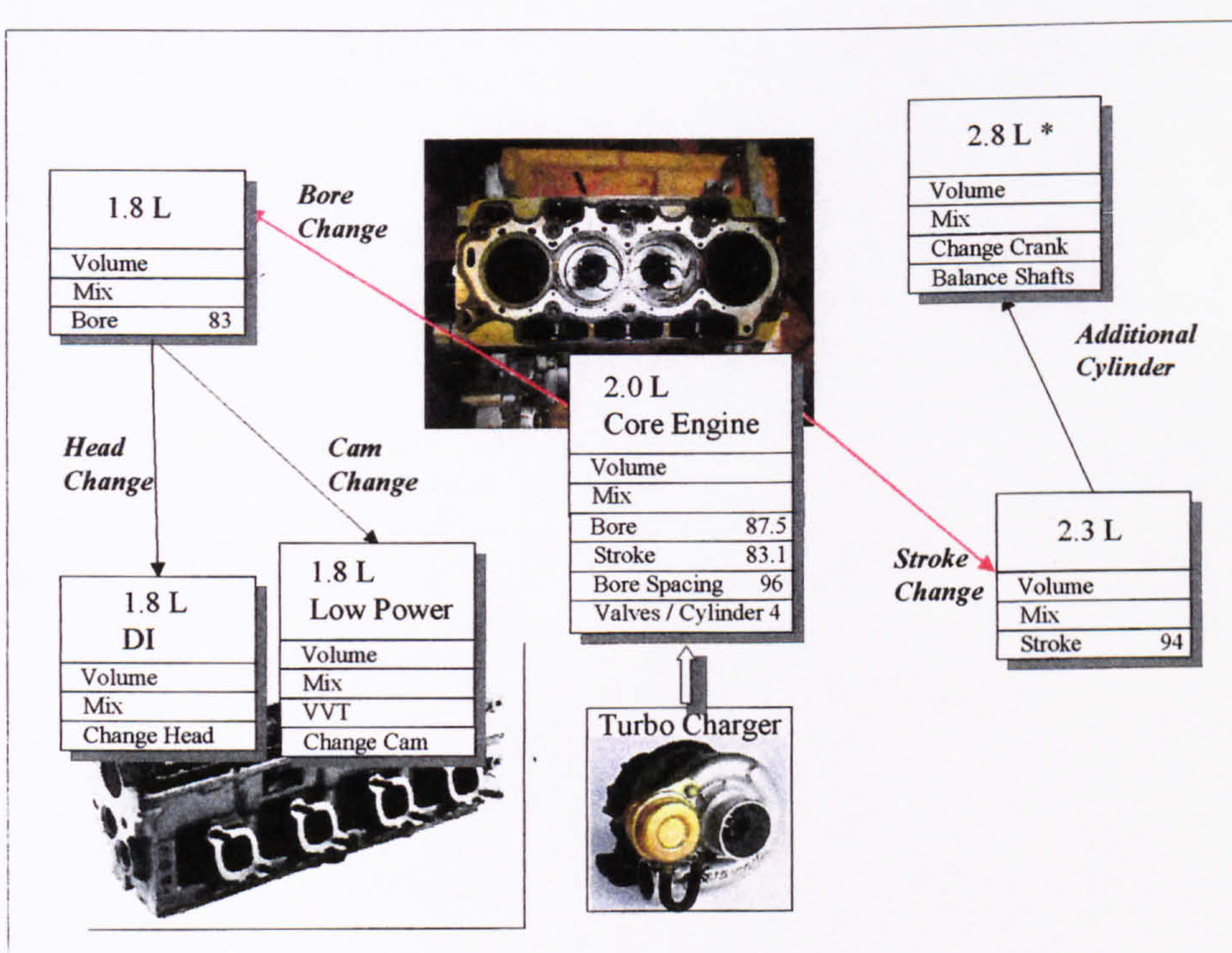
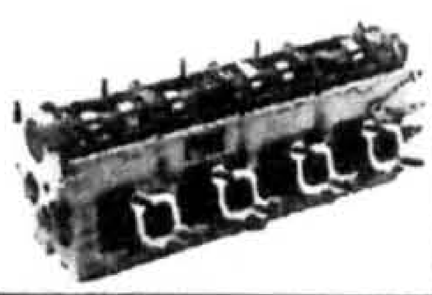
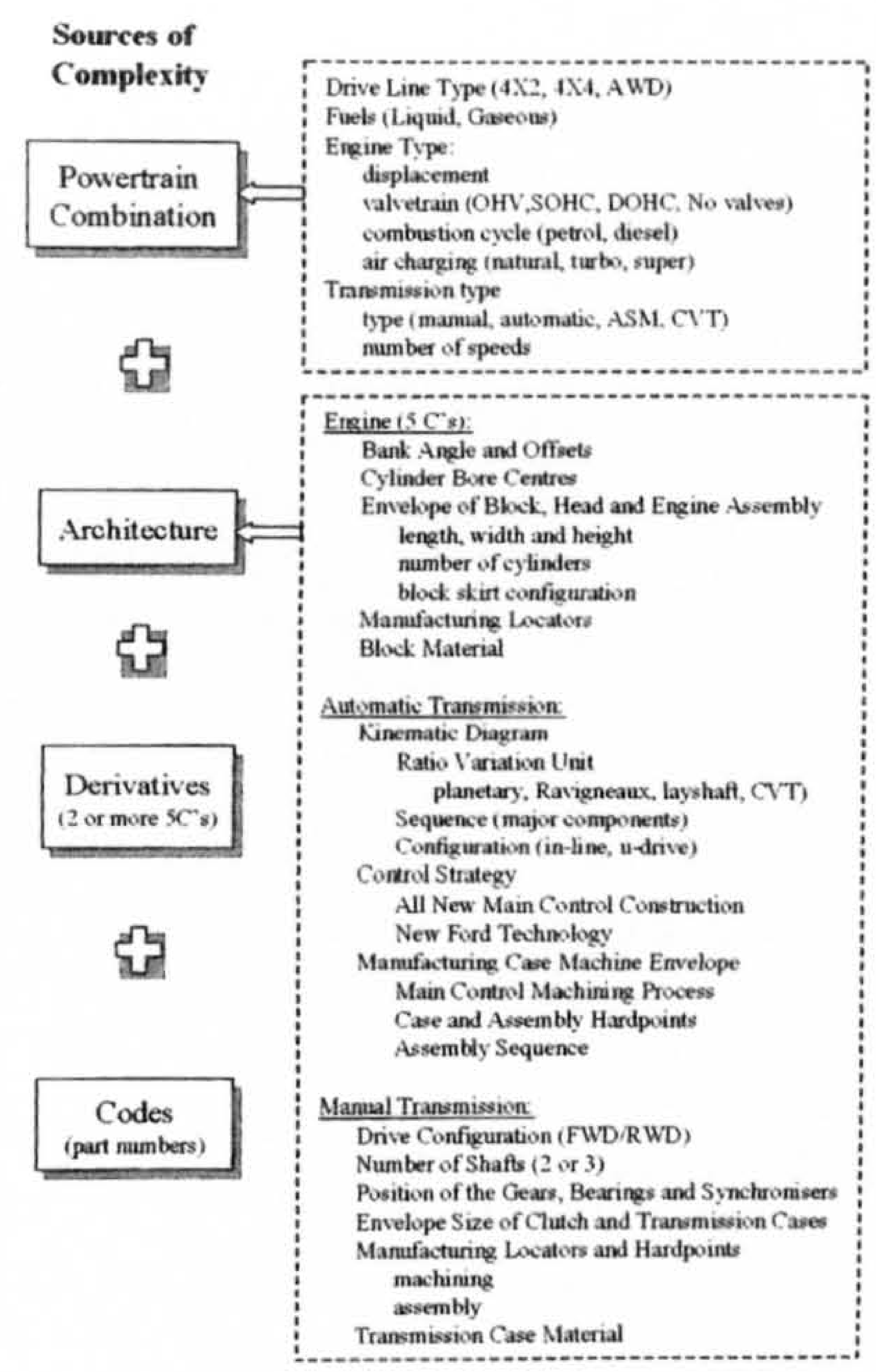


Figure 5-5 Engine Derivative Complexity Mapping



System / Component	"Flexibility" Base 1.8, 2.0 and 2.3 L Engines N(components)	"Agility" (unexpected change) Additional / Reduced Complexity **Mid program**	Total Components Within I4 / I5
Block Assembly – Cylinder	4	0	4
Main Bearing Beam	2	1	3
Cover Assembly – Front	3	4	7
Head Assembly - Cylinder	4	6	10
Crankshaft	3	3	6
Intake Valve	2	2	4
Exhaust Valve	2	2	4
Chain Drive inc Oil Pump	3	-1	2
Camshaft – Intake	10	1	11
Camshaft – Exhaust	7	1	8
Cover – Camshaft Assembly	4	3	7
Connecting Rod Assembly	2	1	3
Piston, Pin and Ring	8	4	12
Intake Manifold Assembly	6	-2	4
Fuel Rail	4	5	9
Exhaust Manifold	10	0	10
FEAD	2	-1	1
Pan-Oil	3	1	4
Pump Assembly – Oil	2	4	6
Water Pump Assembly	2	-1	1



5.2.3 Manufacturing Program Definition

Whilst the Simultaneous Engineering team are defining the scope of the end product, the Manufacturing Program Management staff must determine the Manufacturing Programme Definition specifically; program cost, timing and scope (See Figure 5-6). Detailed timing is established via a top down approach, considering the principal tasks, expected duration and cost constraints. This leads to high level timing definition and finally a detailed work breakdown structure in the form of a proprietary work-planning tool (e.g. Microsoft Project). The Manufacturing Strategy for the program is taken to the next stage of definition by means of a Lean Evaluation Matrix (Figure 5-8). The purpose of the document is to define a current state map in terms of *Lean* manufacturing practices and the future, desired status at the end of the program. The difference between the states is subjected to a gap analysis and appropriate action plans or inhibitors (requiring management support) are identified. The process used to generate the document is illustrated in

Figure 5-9. Each of the 14 categories used to define a lean environment are reviewed by the M-PST and a design objective set. The objective is to set a realistic level that a/ the operational management can achieve and b/ is within the program time and cost targets. The design is evaluated against the objective and a gap analysis created. The Gap Analysis is used by the LCA and STA phases to guide the design. The strategy definition process must be re-visited prior to the design finalisation to establish if the gaps between status and objective have been eliminated or reduced to the minimum possible.

The Program Management group is also charged with providing overall program status to the EST and M-PST groups. A standard set of metrics should be used to facilitate efficient senior management reviews. When collated the metrics form a single page program status covering all the major deliverables of the program. A suggested list of metrics and format for the single page program status are shown in Figure 5-7.

Figure 5-6 Manufacturing Program Definition

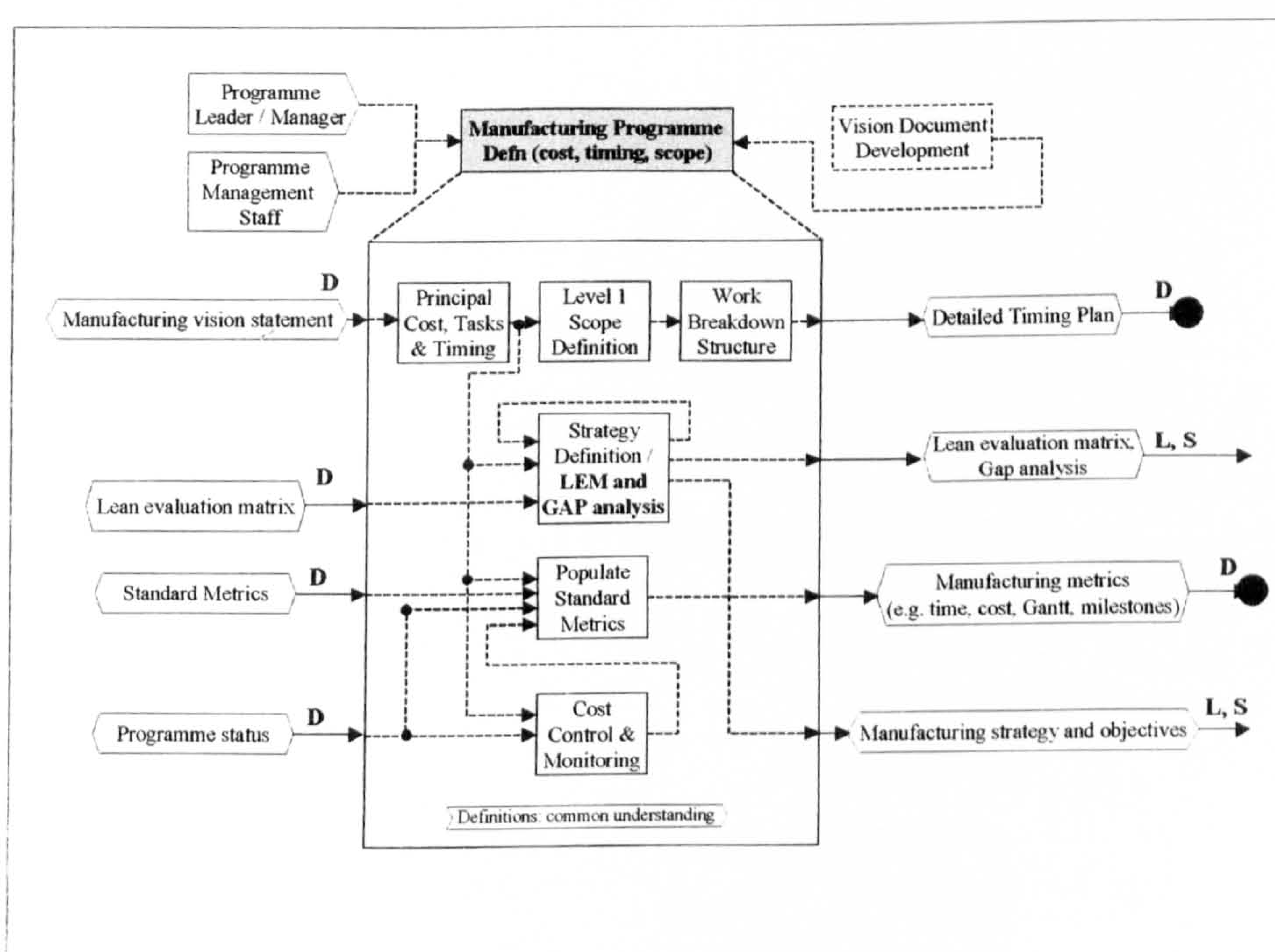


Figure 5-7 Program Metrics and Status Reporting

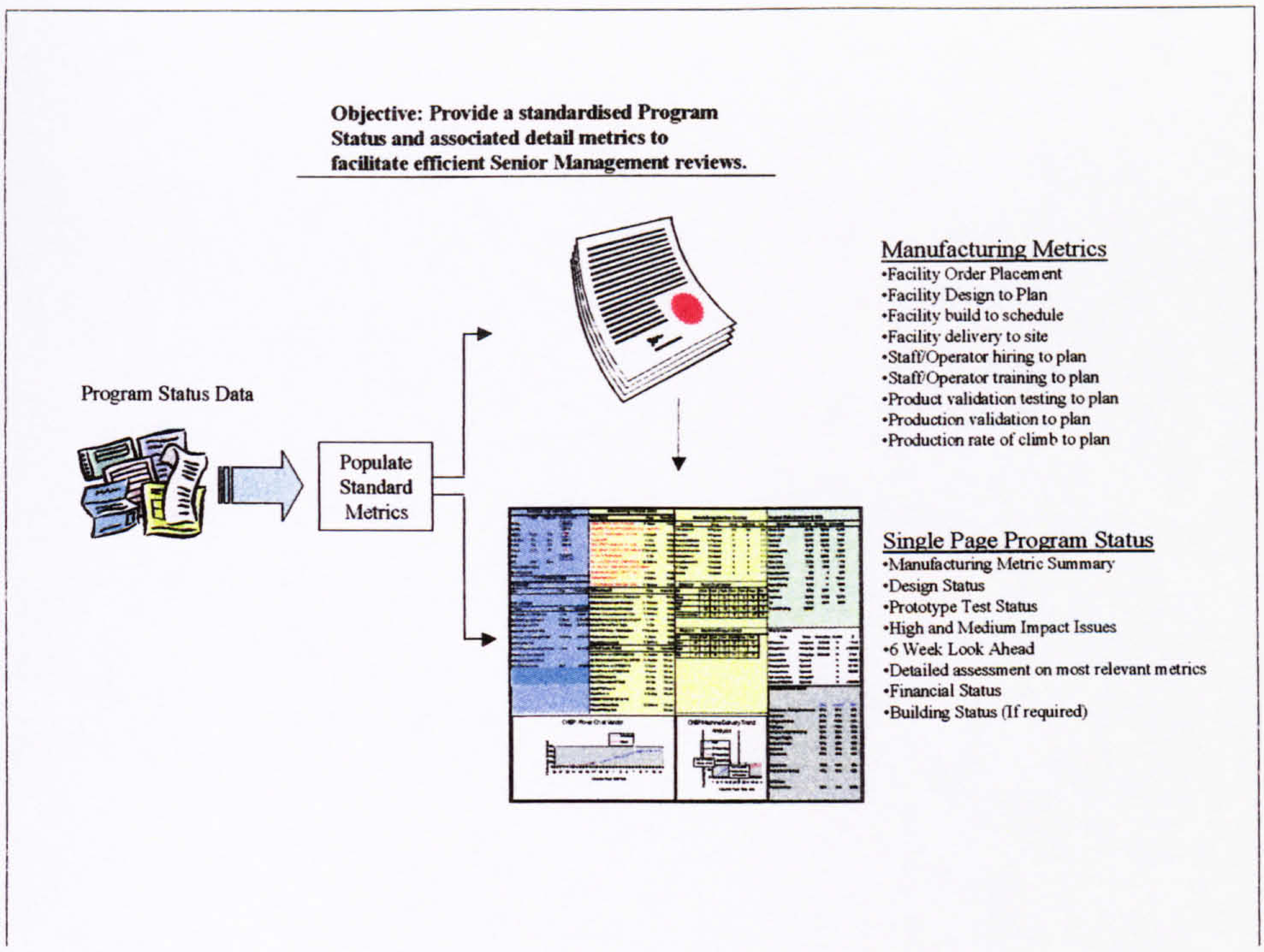


Figure 5-8 Lean Evaluation Matrix

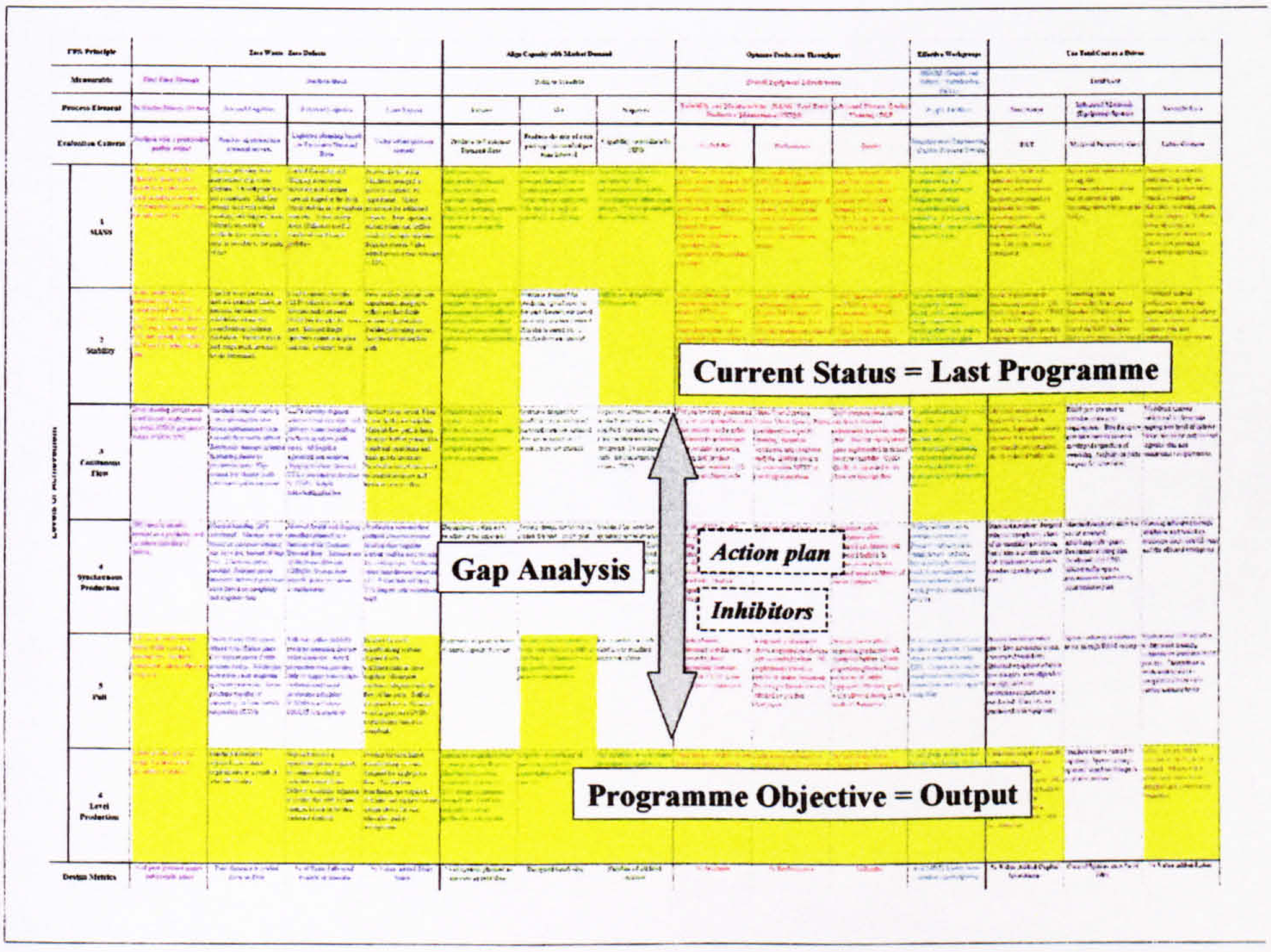
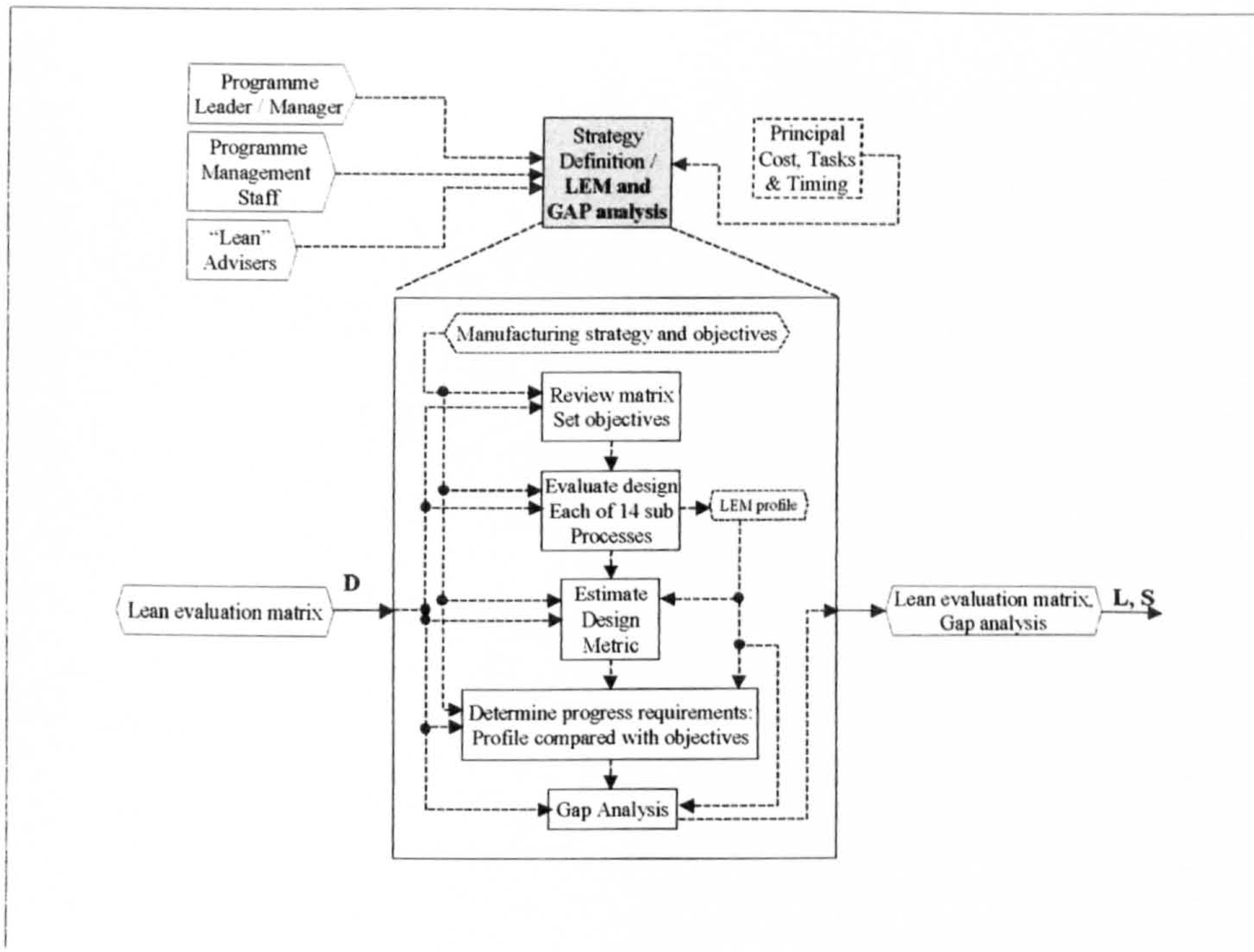


Figure 5-9 Strategy Definition



5.3 Life Cycle Cost Analysis

The second stage of the DRAC is the Life Cycle Analysis. An overview of the four interconnected processes within this environment are shown in Figure 5-10. The aim of LCA process is to initiate the dimensional and process flow planning, identify and prioritise lessons from previous programs, analyse life cycle costing and understand the relationship of the system in terms of reliability and maintainability.

5.3.1 Manufacturing Process Control Planning

The Manufacturing Process Control Planning (M-PCP) requires a completed Design FMEA (D-FMEA) as its primary input. The D-FMEA will identify Critical and Significant characteristics of the design which if not maintained will impact on functionality and hence customer satisfaction. Initially the Critical and Significant Characteristics are used to define a Dimensional Control Plan. The plan will identify the type of control that needs to be applied to maintain an identified product characteristic. A critical characteristic may need closed loop feedback control with gauging to verify process integrity. Often critical characteristics are safety or legislation related for example a design feature that will effect engine emissions or the fastening process that attaches the flywheel to the crankshaft. The resultant output is the Dimensional Control Plan. This acts as an input to the Technical Requirements Analysis as well as a reference document.

Internally within the M-PCP process the output of the Dimensional Control Planning allows the optimum process flow to be established. Evaluation of the Design FMEA and Dimensional Control Plan allows the generation of a Process FMEA and Process Flow Plan.

The completion of this step will in turn allow the Engineering Team to identify the classes of machines and equipment required to fulfil the process requirements. This final stage of the M-PCP also requires input from the Manufacturing Strategy and Objectives, the Lean Evaluation matrix and the product definition in terms of volume and mix. As the evaluation matures feedback from the Life Cycle Costing may influence the class selection. Examples of the each step and the different classes of machine are shown in Figure 5-11.

Figure 5-10 Life Cycle Analysis

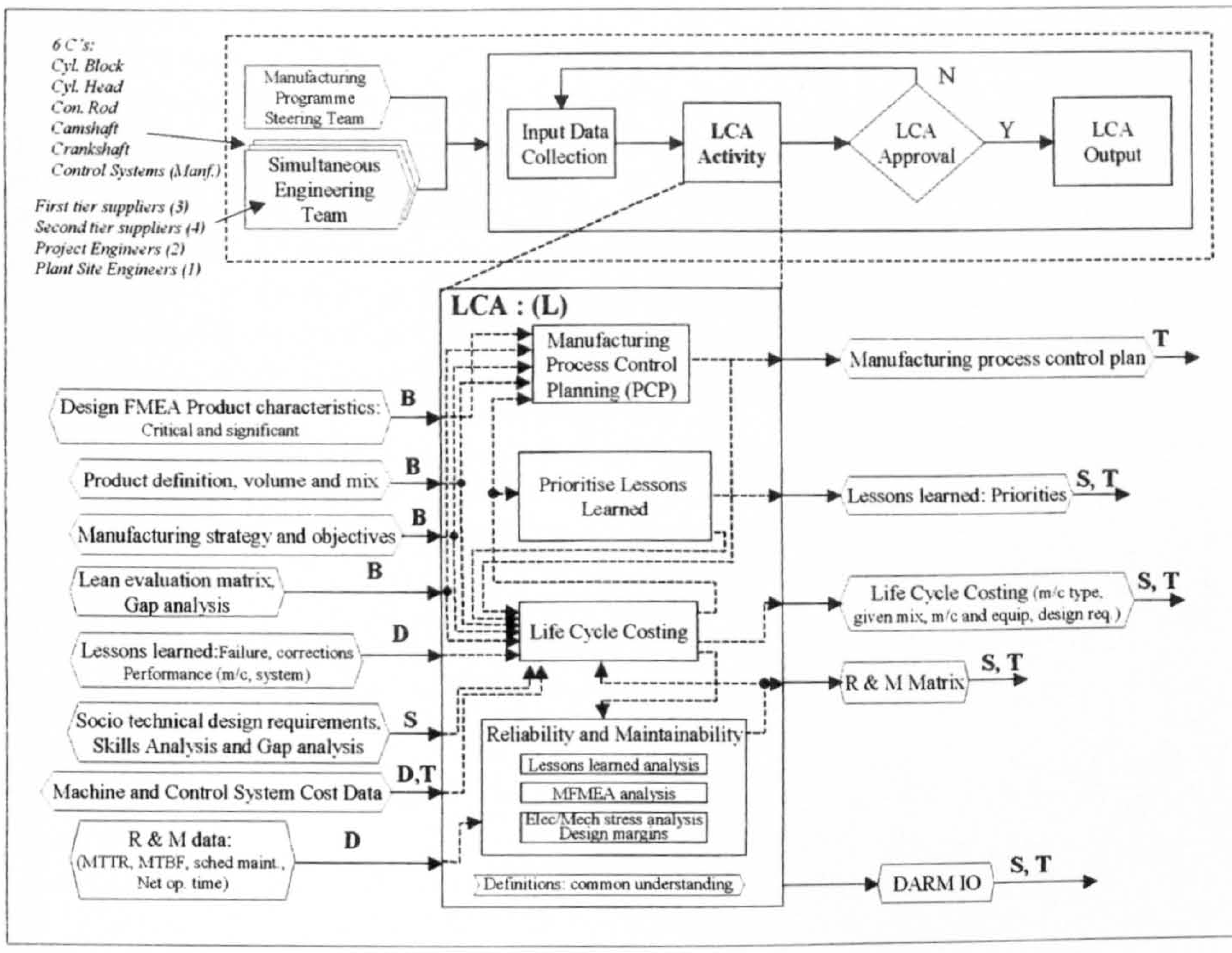
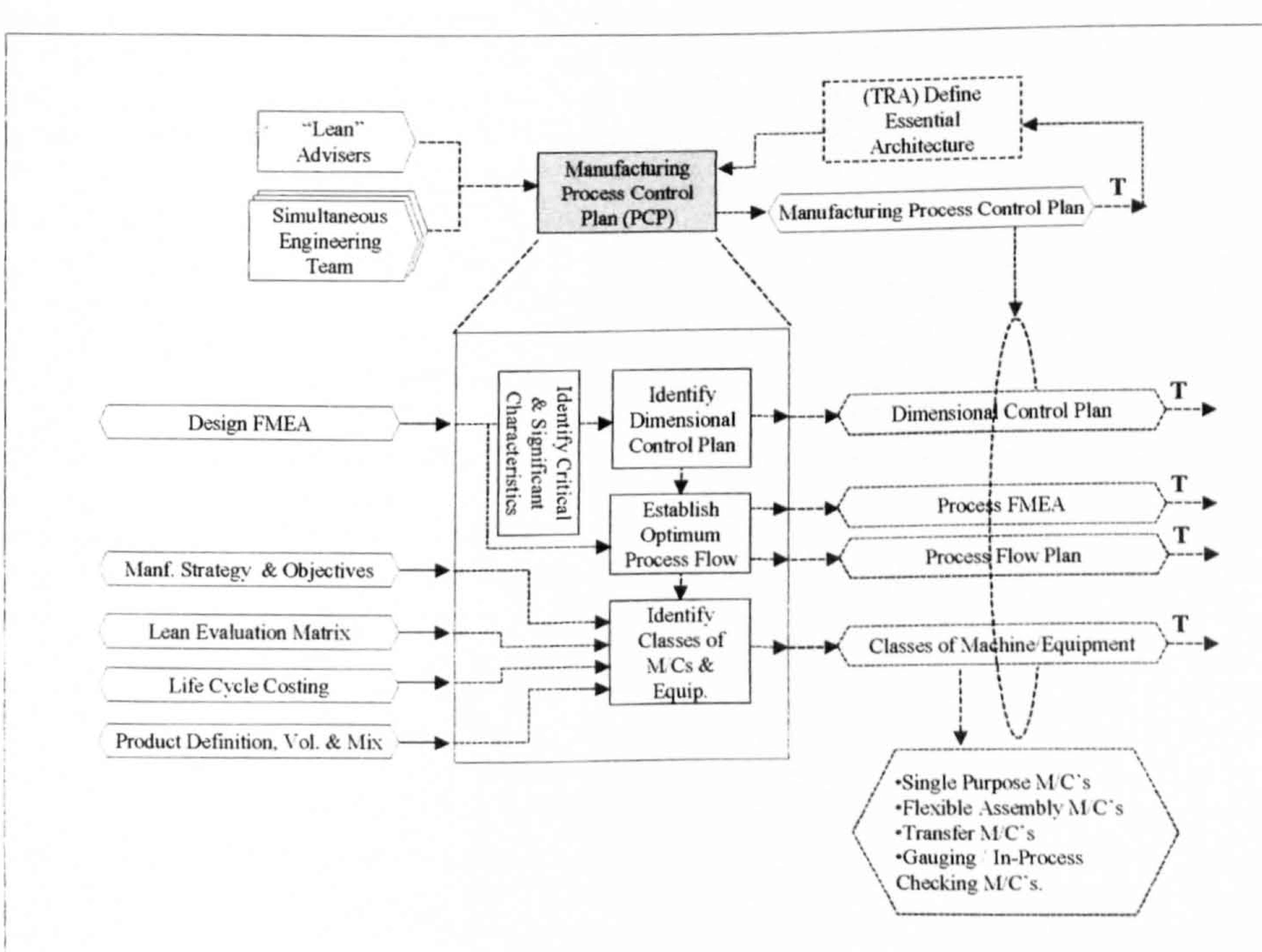


Figure 5-11 Manufacturing Process Control Plan



5.3.2 Lessons Learned Prioritization and Use

An overview of the Lessons Learned process is shown in Figure 5-12. In a global organisation such as those found in the automotive industry it is essential that a process to collect and prioritise new and existing knowledge be established and maintained continually. The process for this continuous activity is shown in some detail in Figure 5-14 and the lifecycle of the *lesson* in Figure 5-13. The knowledge will come from a number of sources, examples include: research and experimentation, use of processes or products and customer feedback. The collection and effective prioritisation of corporate memory is a powerful tool to ensure that previous mistakes are not repeated and good practice replicated. Ideally anyone within the company should have access allowing them to write and enter lessons. All lessons should be forwarded to a clearing house where a specialist with the appropriate technical skills and experience would ensure the lesson is indeed new knowledge and scrutinize the lesson for accuracy, clarity and completeness. The corporate memory or *Lessons Learnt* database must run independently of the needs of a particular program. Many lessons will be missed or wrongly interpreted if the organisation attempts to initiate the process in response to a particular program of work.

Assuming the lesson is approved a central administration area would publish the lesson on the global database. The central administration area would also be responsible for tracking the initial submission and subsequent changes.

In addition to the continuous process described, the program team must initiate a procedure that extracts lessons from the corporate database and identifies those applicable to the program. The listed lessons must then be prioritised and fed to the appropriate areas of design. The *Lesson Learnt Priorities* are listed and where appropriate acted upon during the Socio-technical and Technical Analysis phases.

A typical *lesson* is illustrated in Figure 5-15. The documented recommendation often cannot be taken and directly applied. In the example shown the *lesson* highlights an issue with the training of staff relative to the new control system and calls for training to be completed prior to the first machine arriving on site. The recommended action advocates a reactive response that may solve the problem however a more effective means is to proactively eliminate the concern by significantly reducing the training required (through improved skill matching) and hence eliminate the issue at source.

Figure 5-12 Lessons Learned Process

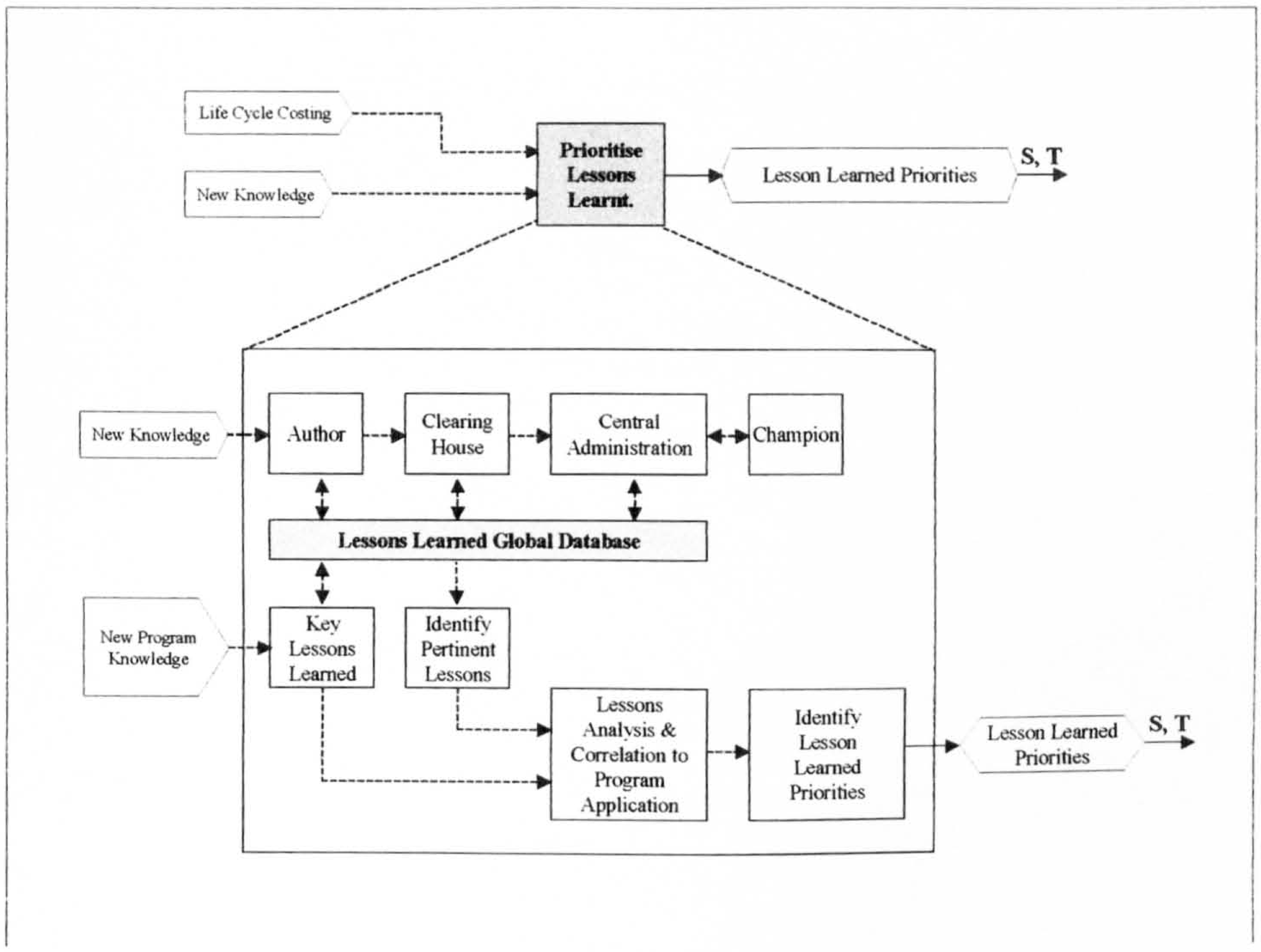


Figure 5-13 Lessons Learned Process Lifecycle

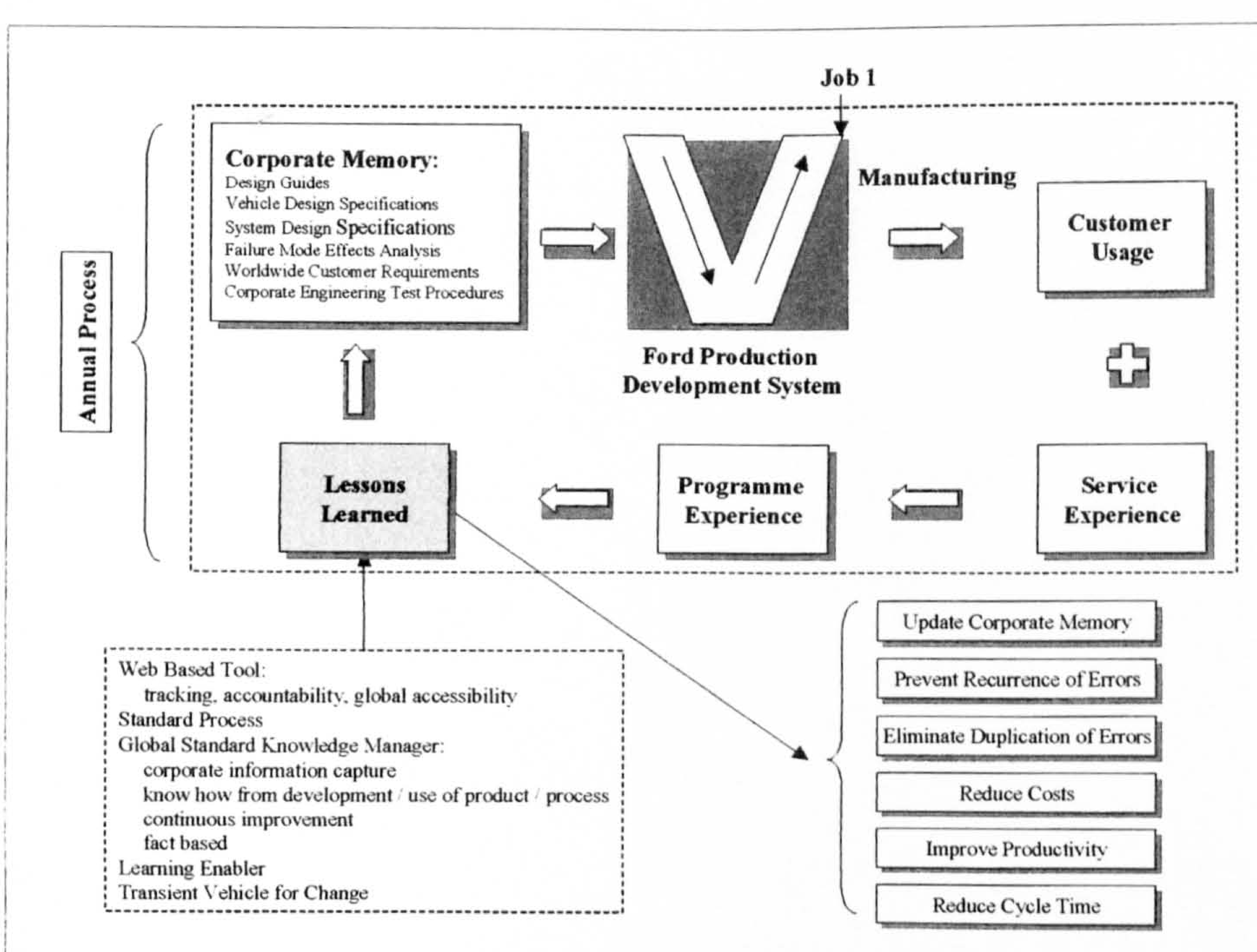


Figure 5-14 Lessons Learned Global Database Process

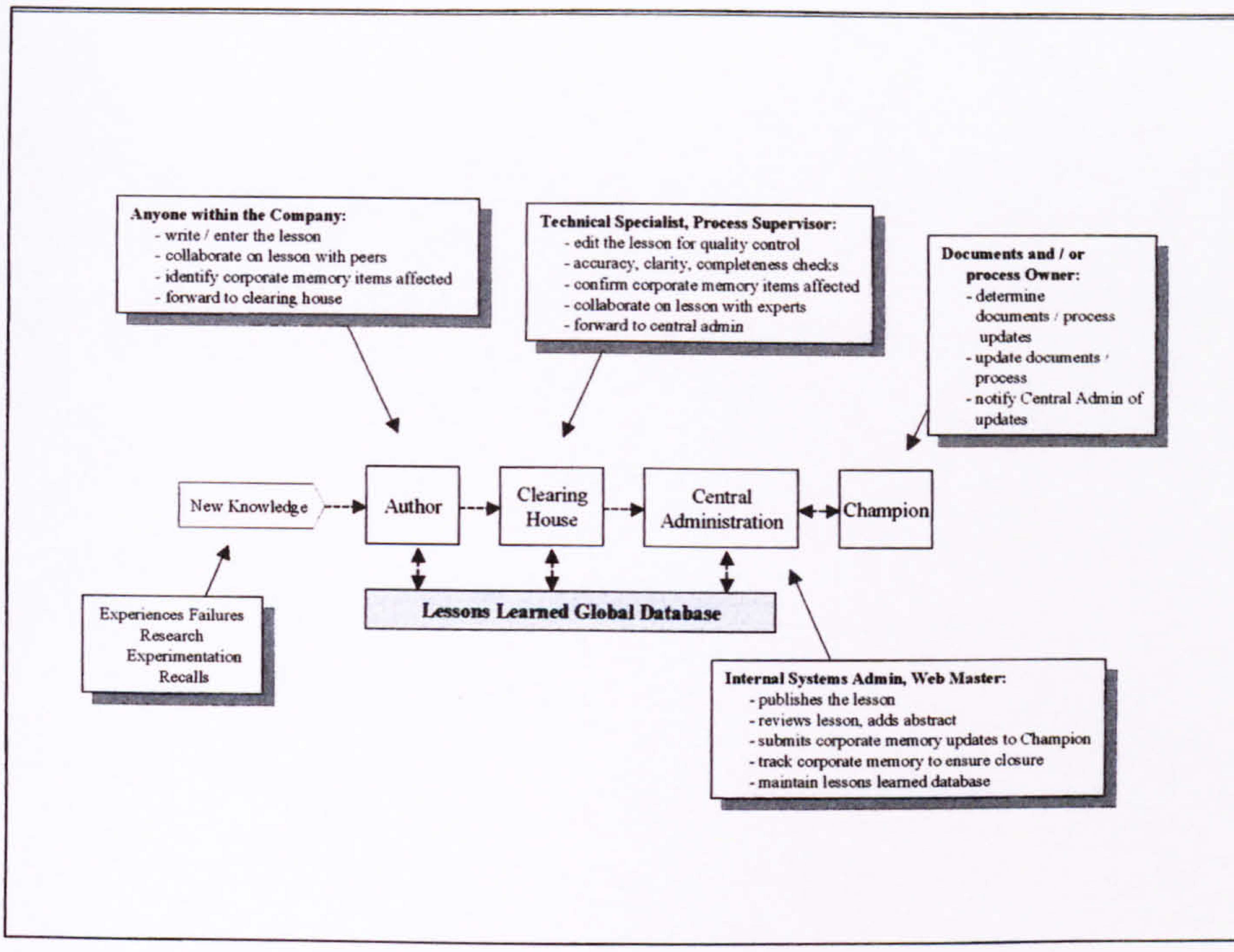
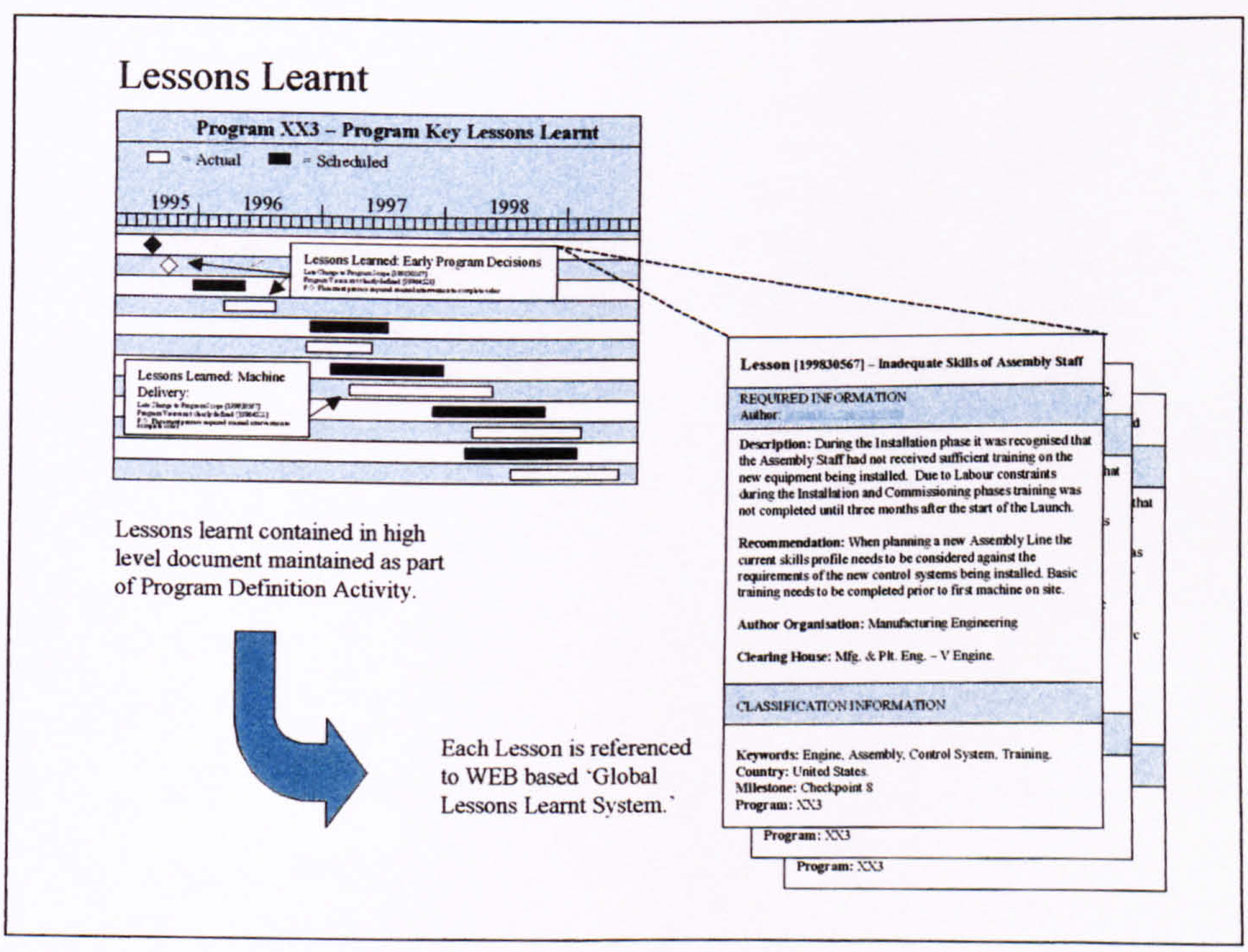


Figure 5-15 Example Lesson



5.3.3 Life Cycle Cost Analysis

The cost of a manufacturing facility is spread throughout its lifecycle. The main areas of cost in the order that they occur are illustrated in Figure 5-16. Acquisition cost is generally the investment associated with procurement including any contract support prior to and during installation and the cost to apply the system. Often organisations mistakenly focus almost exclusively on this area: a/ because it has an immediate effect on the companies finances and b/ because it is easy to measure, (unlike some of the ownership costs). Cost of Ownership includes the cost of operations and maintenance, which in the case of automotive users can vary between eight and fifteen years. The costs incurred during this period normally far outweigh the purchase cost and as such should receive an appropriate amount of attention. The need for flexible, adaptable facilities increases the importance of the final part of the Life Cycle costing, namely the cost to convert facilities mid way through their life. In many countries the disposal of equipment is now strictly controlled increasing the need to consider costs related to the eventual disposal of the equipment. The majority of opportunities to minimise Life Cycle Cost are locked in to the system in the first third of the program design and installation cycle, (see Figure 5-17). It is therefore crucial that the program management team organise a *Life Cycle Cost* critical design review early in the program design process.

The overall Life Cycle costing process is illustrated in Figure 5-18. The author proposes the use of an agreed Life Cycle cost model in the form of a spreadsheet application. The model is used to calculate the control system life cycle cost as a function of investment, operating and maintenance cost over the facilities useful life. A typical LCC model is shown in Appendix B. The model design and data input requires detailed knowledge of the manufacturing operation, where the system will be used, and relevant data that can be used to quantify costs. Maintenance cost will be influenced by equipment reliability, mean time to repair and the suitability of the system when matched with the skill levels and operating practices utilised in the plant.

The application of the model involves a more complex process than initially indicated by the spreadsheet. An example of this complexity can be illustrated by considering the MTTR. In its simplest form the reported MTTR is based upon the historical data for that machine type, the complexity of the machine (e.g. number of stations, specialist gauging.) and level of diagnostics. This provides a sound basis for the evaluation, however an allowance for the Production System Model (Chapter 2) and Workgroup structure (see Figure 2-3) must be made; both will influence the response time to the repair and hence calculations within the model. The outputs from the LCC analysis are fed to the Socio-technical and Technical analysis phases.

Figure 5-16 Life Cycle Cost Elements

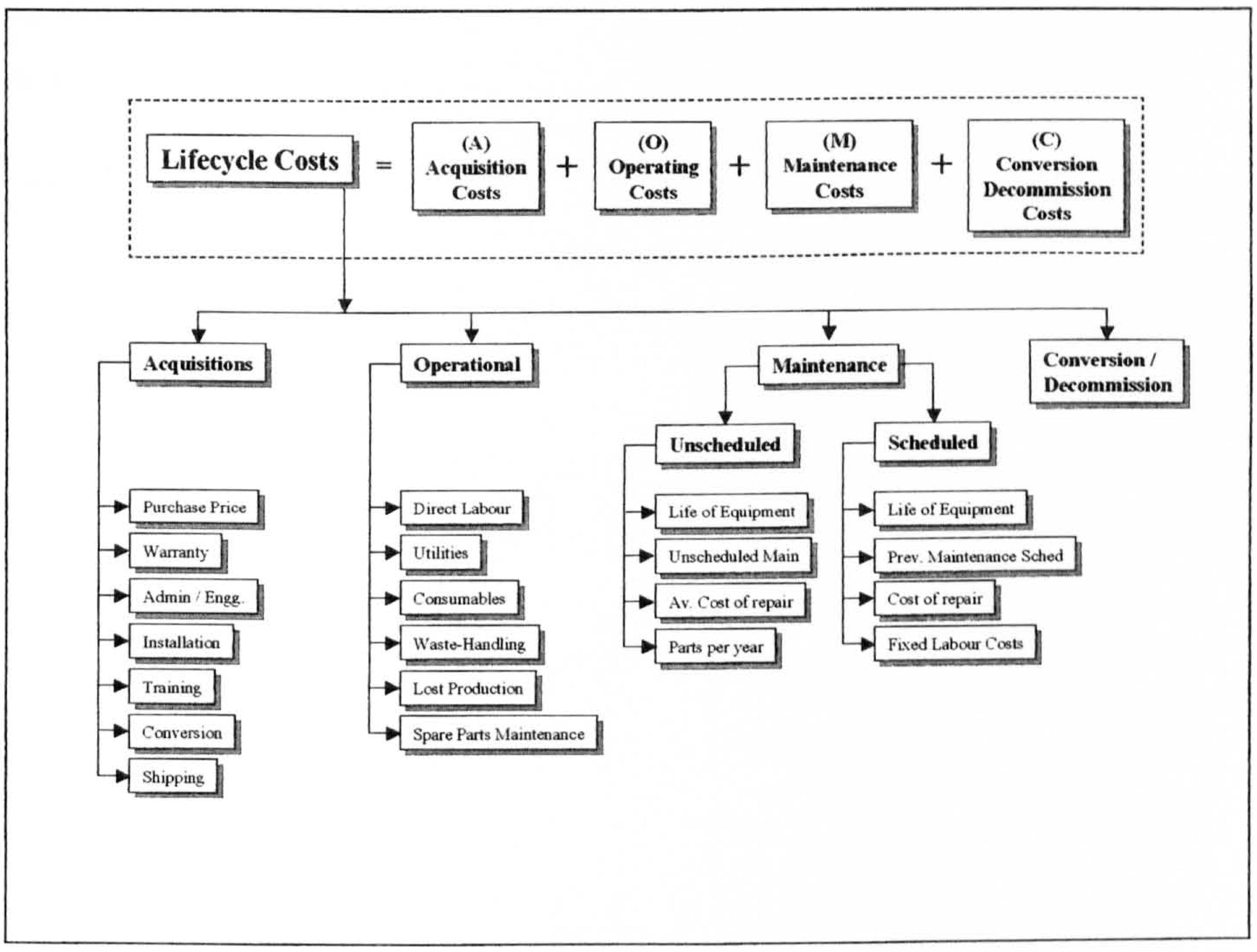


Figure 5-17 Life Cycle Cost Drivers

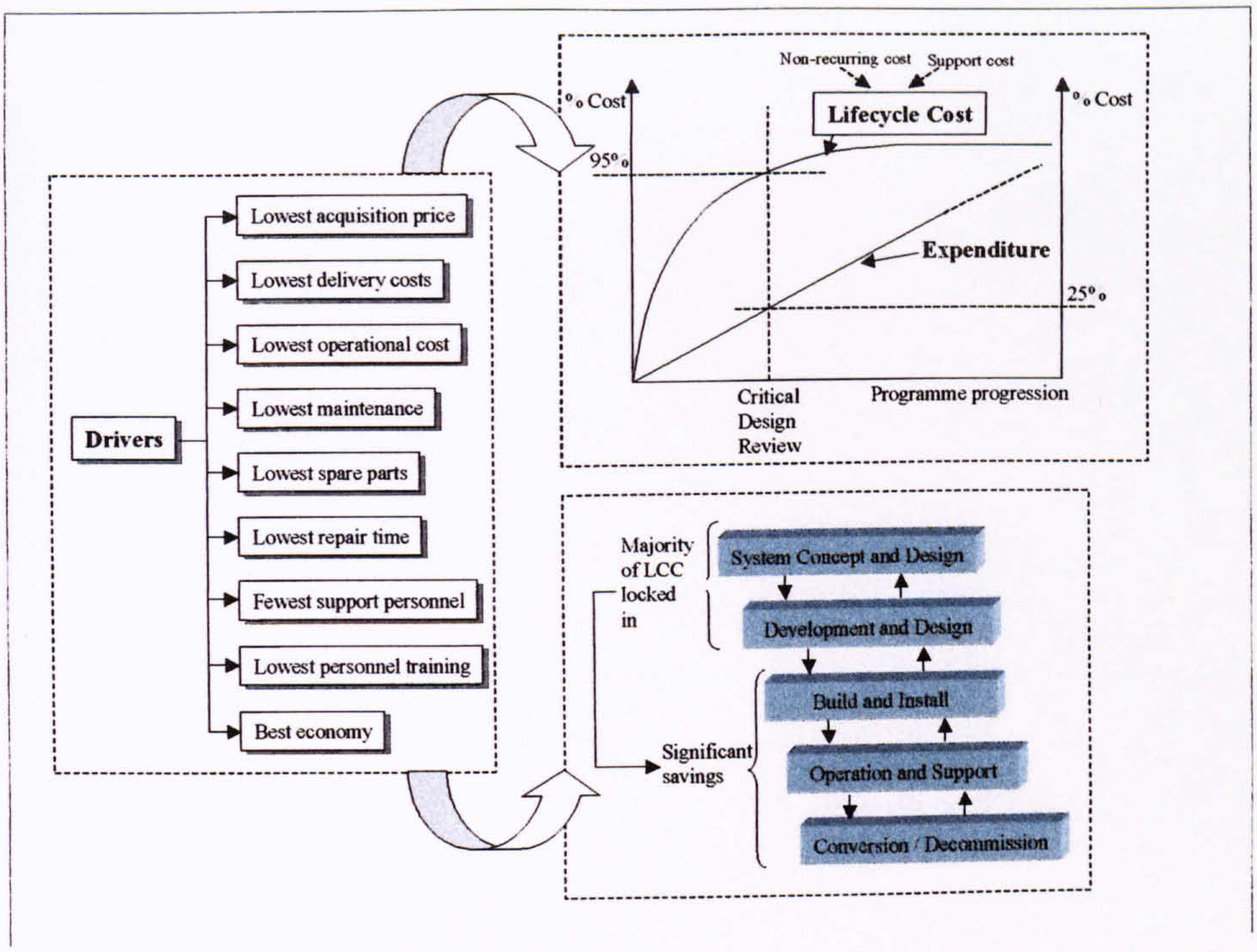
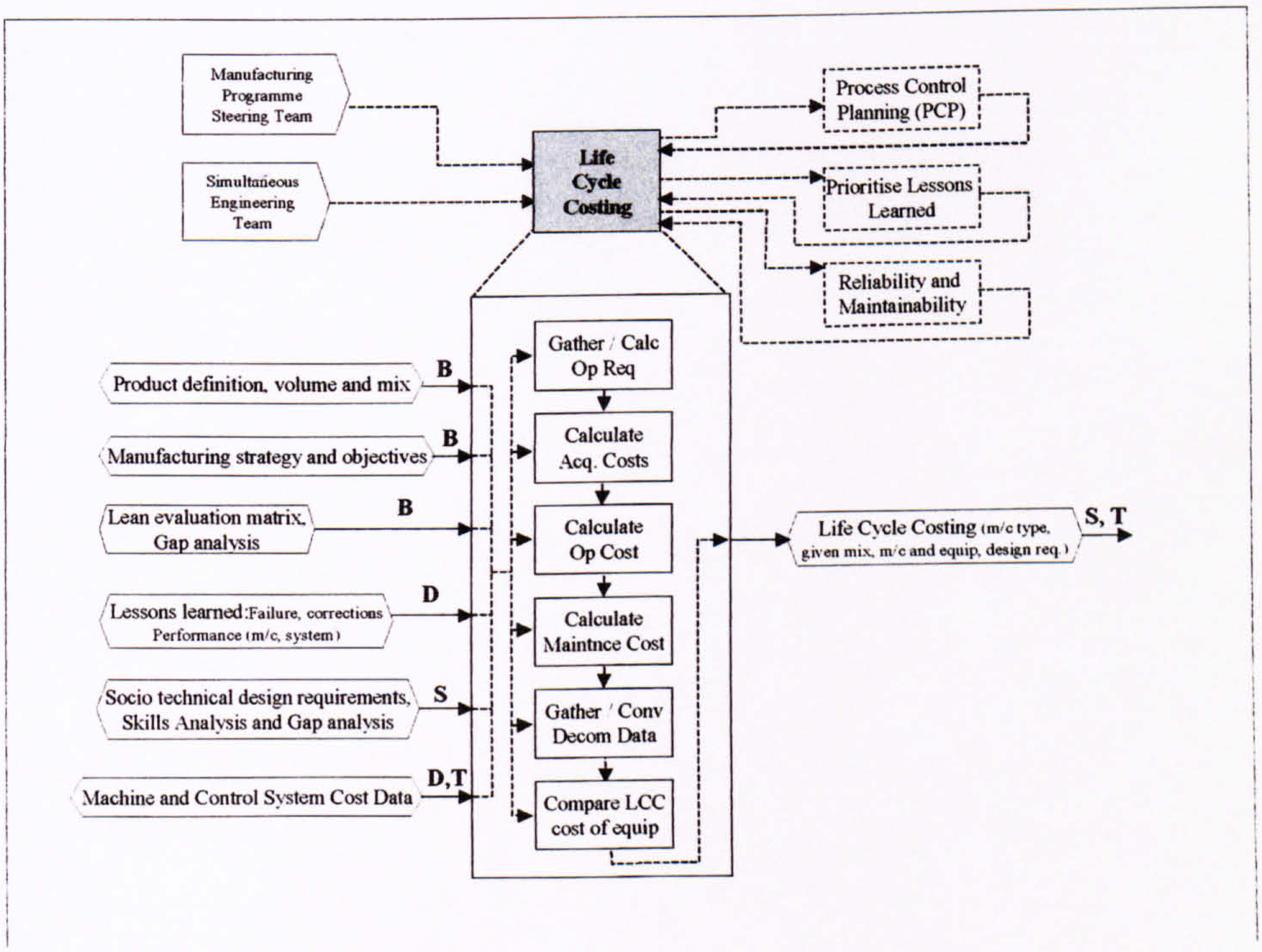


Figure 5-18 Life Cycle Costing



5.3.4 Reliability and Maintainability Analysis

The final step of the Life Cycle Cost process is to establish requirements and design objectives in terms of Reliability and Maintainability (R&M). The operational effects of production shortfalls and the inability to predict downtime are significant. These include unscheduled overtime, unplanned and increased maintenance requirements and costs, and excessive work in process around constraint operations. Due to a lack of confidence in the performance of equipment, many end users purchase additional facilities, tooling and spares in order to meet production requirements.

Accurately forecasting the performance of machinery plays a key part in driving waste out of the manufacturing system therefore; the aim of the R&M analysis shown in Figure 5-19 is to improve the predicted level of machinery performance. This must be combined with an understanding of how machine performance can be increased providing greater reliability and by doing so making a significant contribution to the aim of lowest total cost. The R&M process relies to a great extent on historical data generated by equipment suppliers and the manufacturing plant. Inputs to the process include historical equipment failure database, tear down reports and fault tree analysis. Although the prime objective is to increase reliability, inevitably failures will occur therefore the speed and ease of equipment maintenance must also be considered.

The R&M Design Review process results in a set of design recommendations that are captured as design requirements and recommendations. The implementation of the recommendations and activity, responsibilities are documented in an R&M Activity Matrix (see Figure 5-20). The outputs from the process are fed to the Socio-technical and Technical phases of the DRAC.

Figure 5-19 Reliability and Maintainability Process

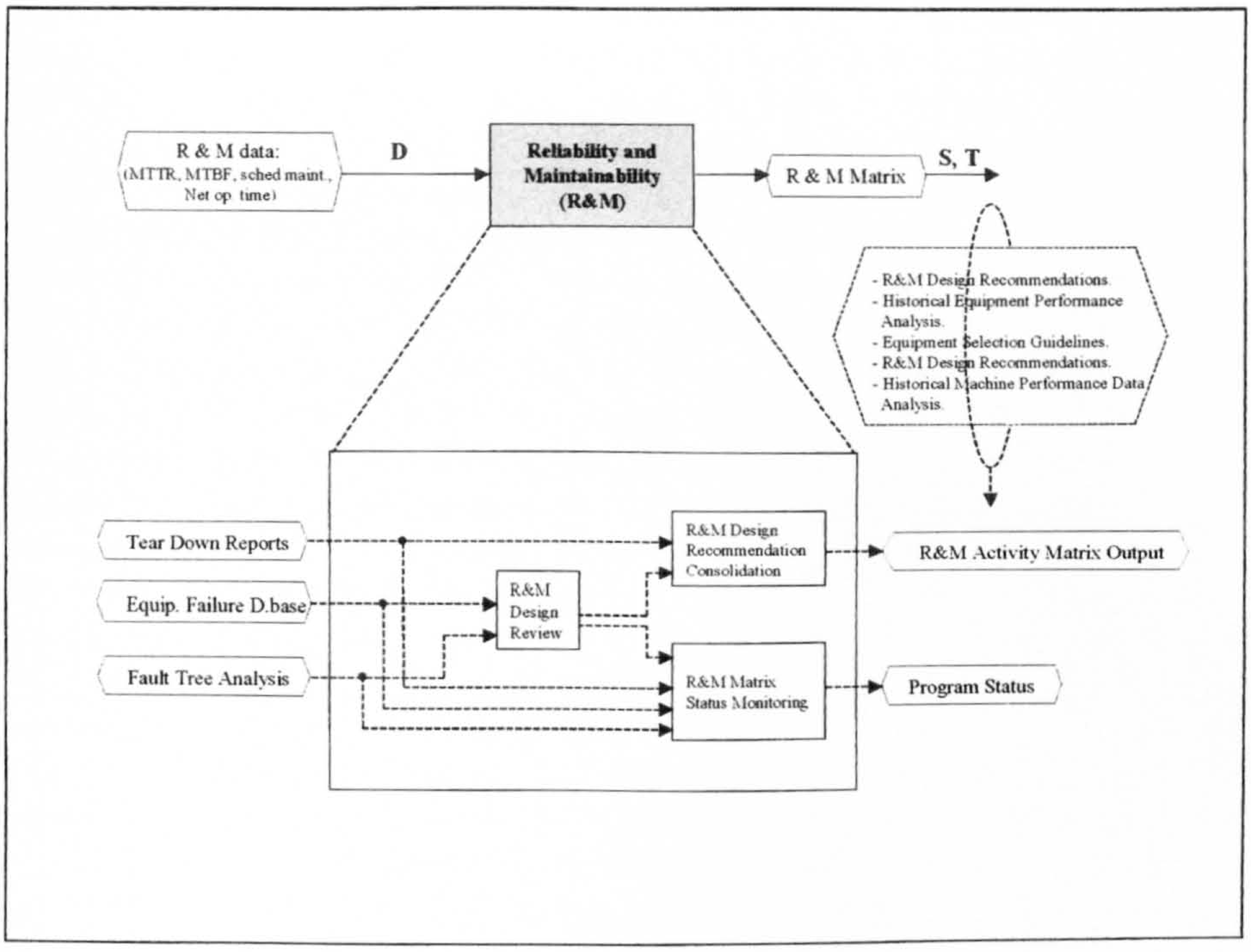
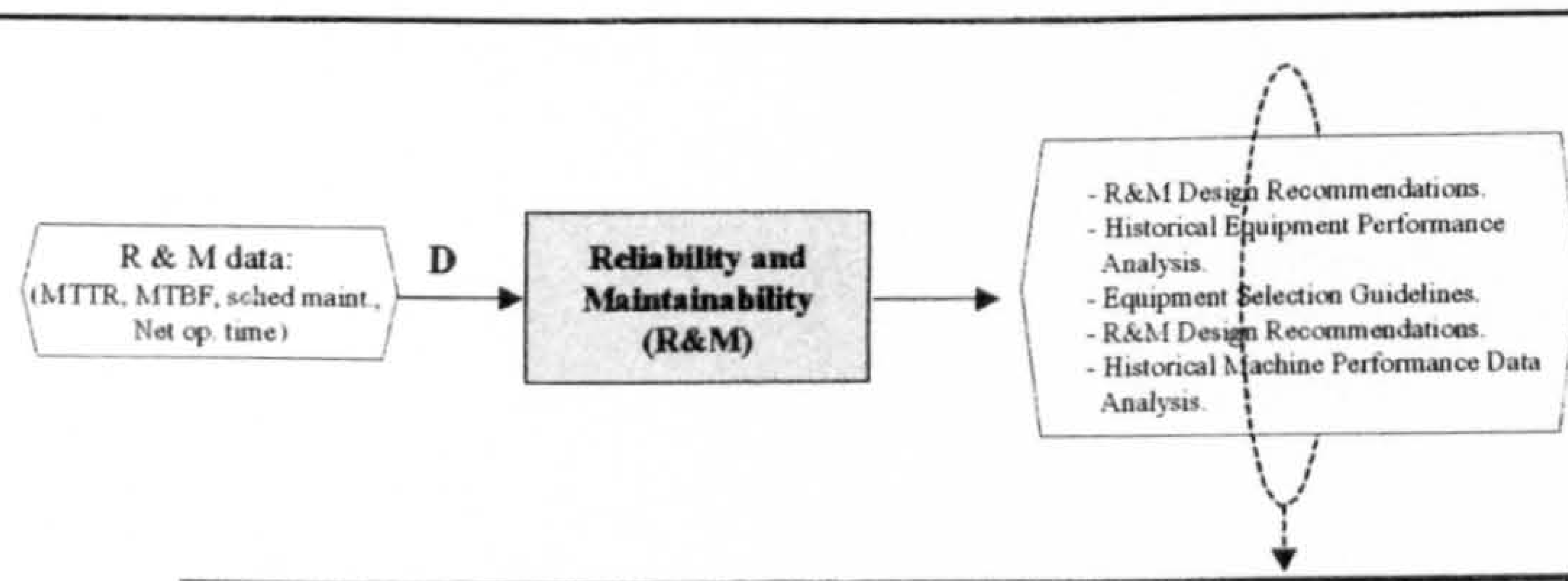


Figure 5-20 Reliability and Maintainability Activity Matrix



R&M Activity Matrix		Lead/Support Responsibility L = Lead S = Support				Design Phase	
R&M Inputs	Activity	Manf. Eng.	Plant Operator	R&M Eng.	OEM	C = Concept D = Design BI = Build/Install Op = Operation ReU = Reuse	Principle Outputs
Existing Equipment.	Tear Down & Measure	S	S	L	L	C	Tear Down Analysis
Equipment Failure database	Equipment Failure Recording Process -	S L L S S	S S S S S	L S S L L	L L L S S	C D BI Op ReU	Historical Equipment performance data analysis. Equipment selection guidelines.
Output of 2,4	R&M Design Review	L L S	S S S	S S L	L L L	C D Op	R&M Design Recommendations
Machine Stoppages Data Collection	Fault Tree Analysis	L L L S S	S S S S S	S S S L L	L L S S L	C D BI Op ReU	Historical Machine performance data analysis and Machine Design recommendations.
Status on items 1-5 above	R&M Matrix Management	L L L S S	S S S S S	S S S L L	S S S S S	C D BI Op ReU	Tracking of R&M matrix

5.4 Socio-technical Analysis

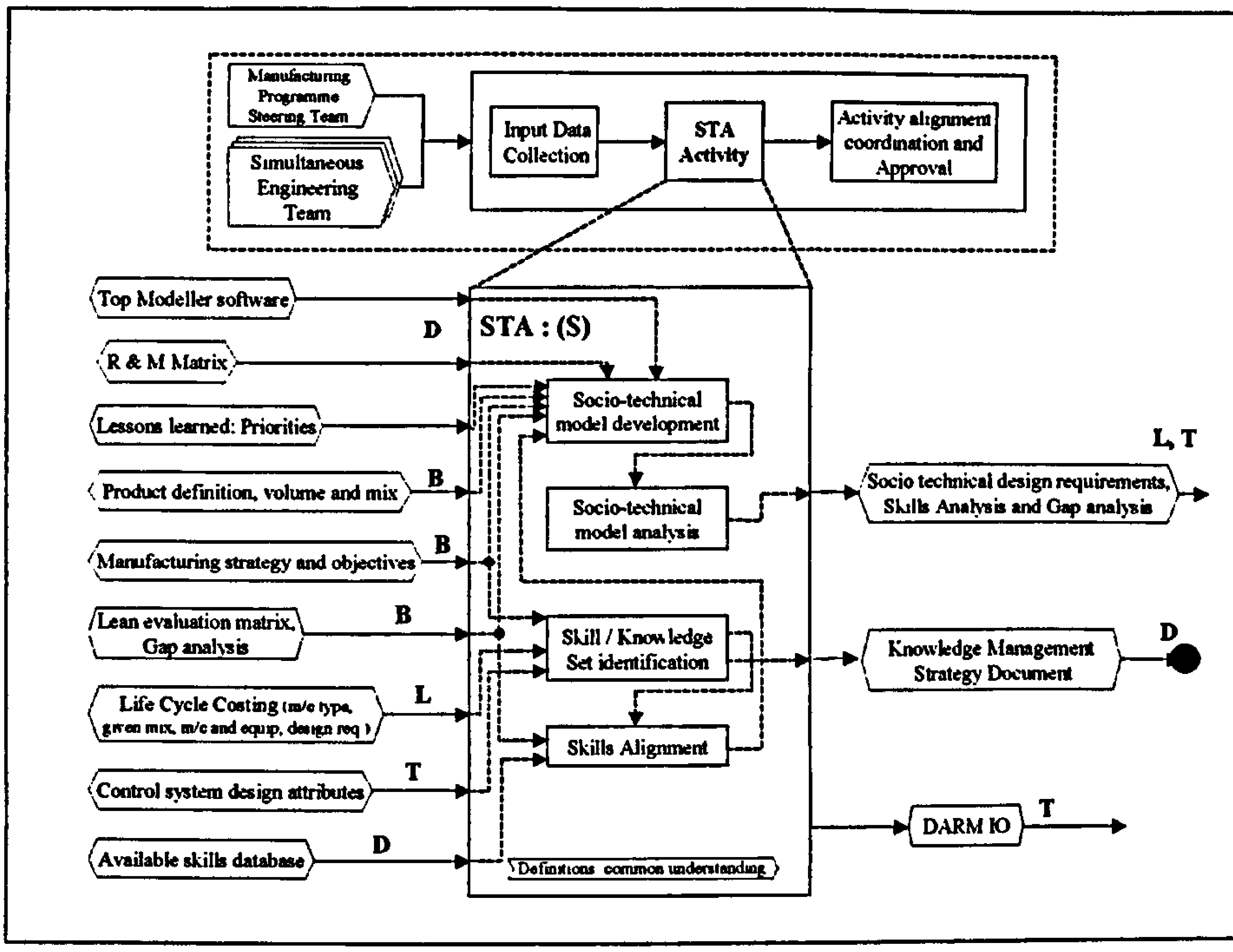
The NGC design philosophy promotes a view that no one element can be taken alone and modified without affecting other elements of the system design. The Socio-technical Activity (STA) phase of DRAC is key to the realisation of this principle. The two processes are shown in Figure 5-21, i.e. Socio-technical model development and analysis; and Skill set identification and alignment.. The STA process actively promotes the notion that organisational systems function effectively and proactively if the elements are compatible and integrated with the technical characteristics of the design. The presence of these interdependencies requires that the STA design methodology be addressed after the initial definition of Business and Life Cycle Cost strategies and prior to the reference architecture and physical definition identified during the Technical Requirements Analysis (TRA).

The aims of the Socio-technical analysis are:

- To align strategic, organisational design, and human resource variables identified in the domain analysis,
- To order and weight the variables,
- To define relationships between the variables,
- To identify and prioritise Socio-technical features that need to be addressed in the Technical Design analysis.
- Identify skill availability and match these with those required to operate and maintain the design.

The aims are collectively represented in the STA output, namely the Socio technical design requirements, Skills Gap Analysis.

Figure 5-21 Socio-technical Process Overview

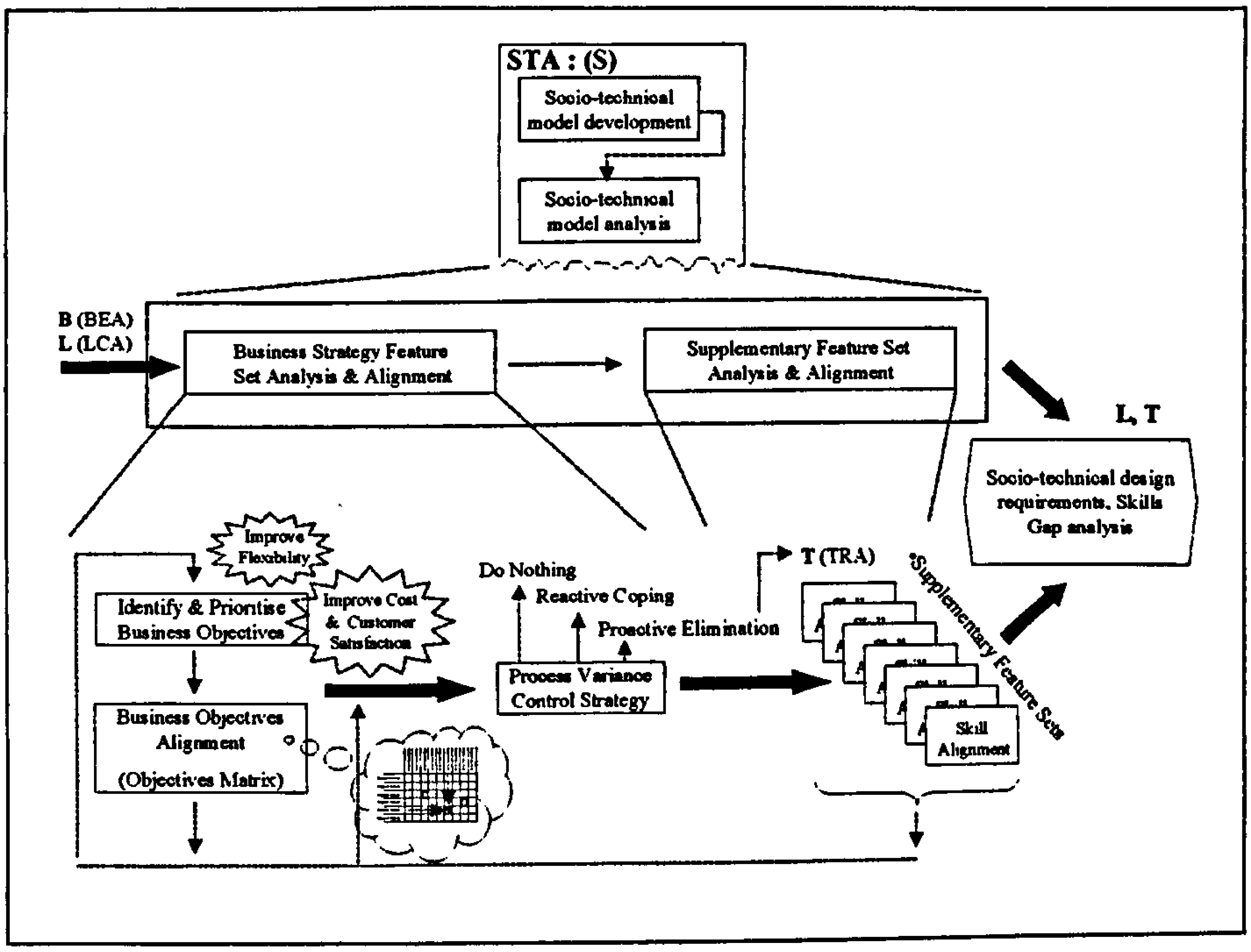


5.4.1 Socio-technical Model Development and Analysis

To manage the large and complex set of variables present at this stage of the process the author proposes the use of a modelling tool that allows the simultaneous analysis and alignment of strategic, organisational, technological, and human resource features against a set of ideal conditions. The ideal conditions must come from a large, well-validated base of scientific and best-practice knowledge of *lean* manufacturing practices. A number of *feature sets* are required to cover the various facets of the Business and Operating environment. The example given in Figure 5-22 demonstrates the sequential steps to define the environment.

For the purposes of this application study the author utilises a proprietary modelling tool, (Top Modeller™) that provides 14 *Features Sets* (see Figure 5-23) to describe an organisation.

Figure 5-22 Socio-technical Model Development and Analysis



5.4.2 Business Strategy Feature Sets

Three initial *feature sets* define Business Strategies based on the criteria, variables and relationships identified in the Business Environment and Life Cycle Analysis. The *feature sets* are: Business Objectives, Process Variance Control Strategies and Organisational Values. A series of questions help the user identify two types of objectives: those intended to reduce cost while simultaneously improving customer satisfaction, and those intended to enhance the organisation's future adaptability. In the Automotive industry it is often the case that the organisation will endeavour to improve on three key measurable, namely minimising throughput time, maximising quality first time through, and/or maximising changeover flexibility (e.g. minimising set-up time).

Each business objective defined in the model is examined and the most appropriate selected. Many of the business objectives, allow the design team to indicate not only if a feature is critical or not, but also the scope of operations considered within the application contaxt of this Thesis, (ranging from a narrow scope of individual operations to a broad scope of the entire assembly line). With the objectives selected, the *Objectives Matrix* shown in Figure 5-25 is used to identify the degree of misalignment among the selected objectives.

5.4.3 Process Variance Control Strategies

The second modelling step is to select the Process Variance Control Strategies. Process Variances are defined as technical variations (planned or unplanned) in the production work flow that creates uncertainty in the processing of materials. The team is asked to indicate if a process variance is *Not of Concern* to the operation; this being the case, then that variable is selected. If the process variance is of concern, then, the design team is asked to indicate their strategy (intention) for controlling that variance, for example:

- Do nothing,
- Expect the employees in the manufacturing team to react to a process variance effectively when it occurs, but not to actively work to reduce its effect (*Effective Reactive Coping),*
- Attempt to reduce its effect rather than to cope with it, (*Proactive Elimination).*

Figure 5-23 TOP Modeller Feature Sets

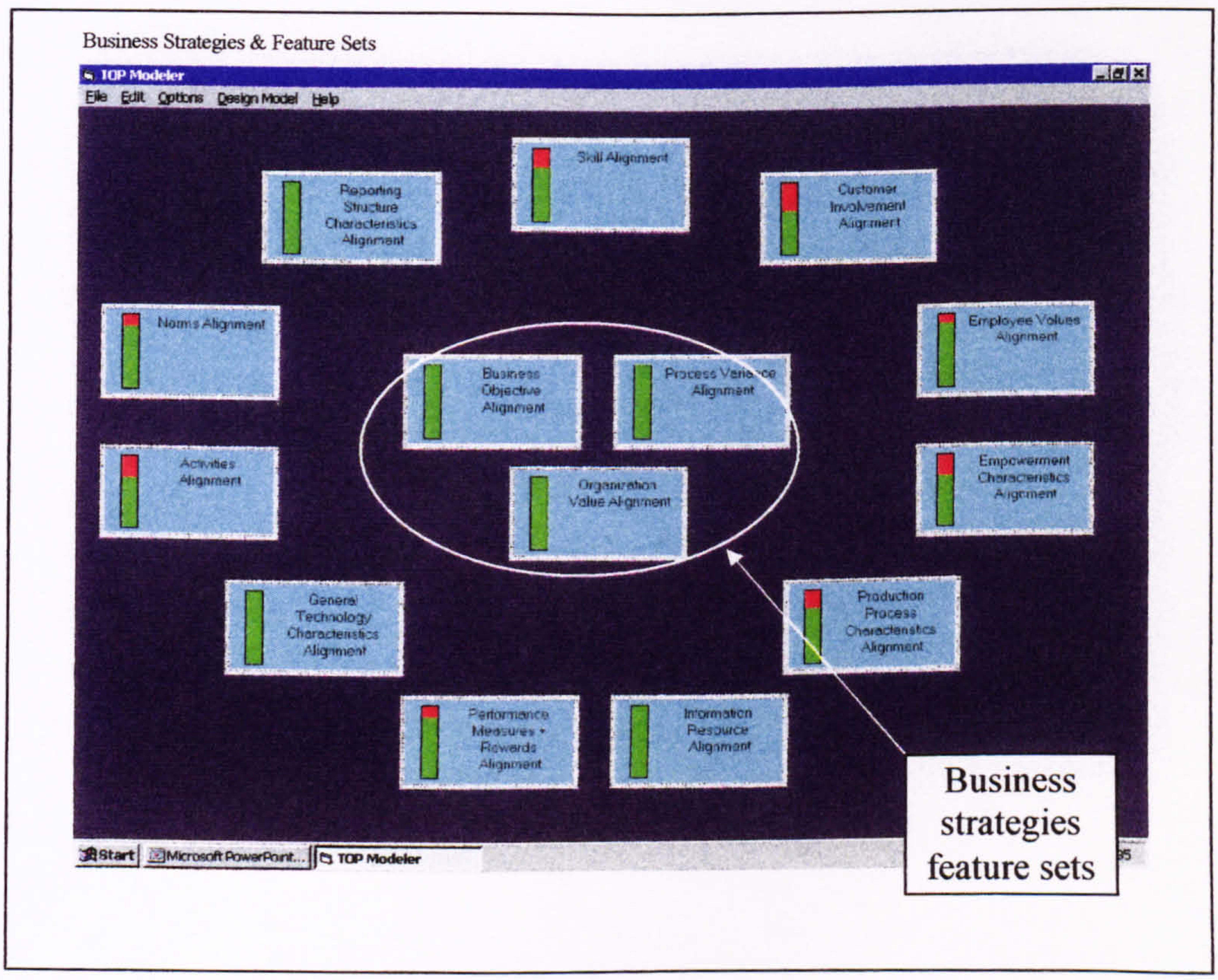
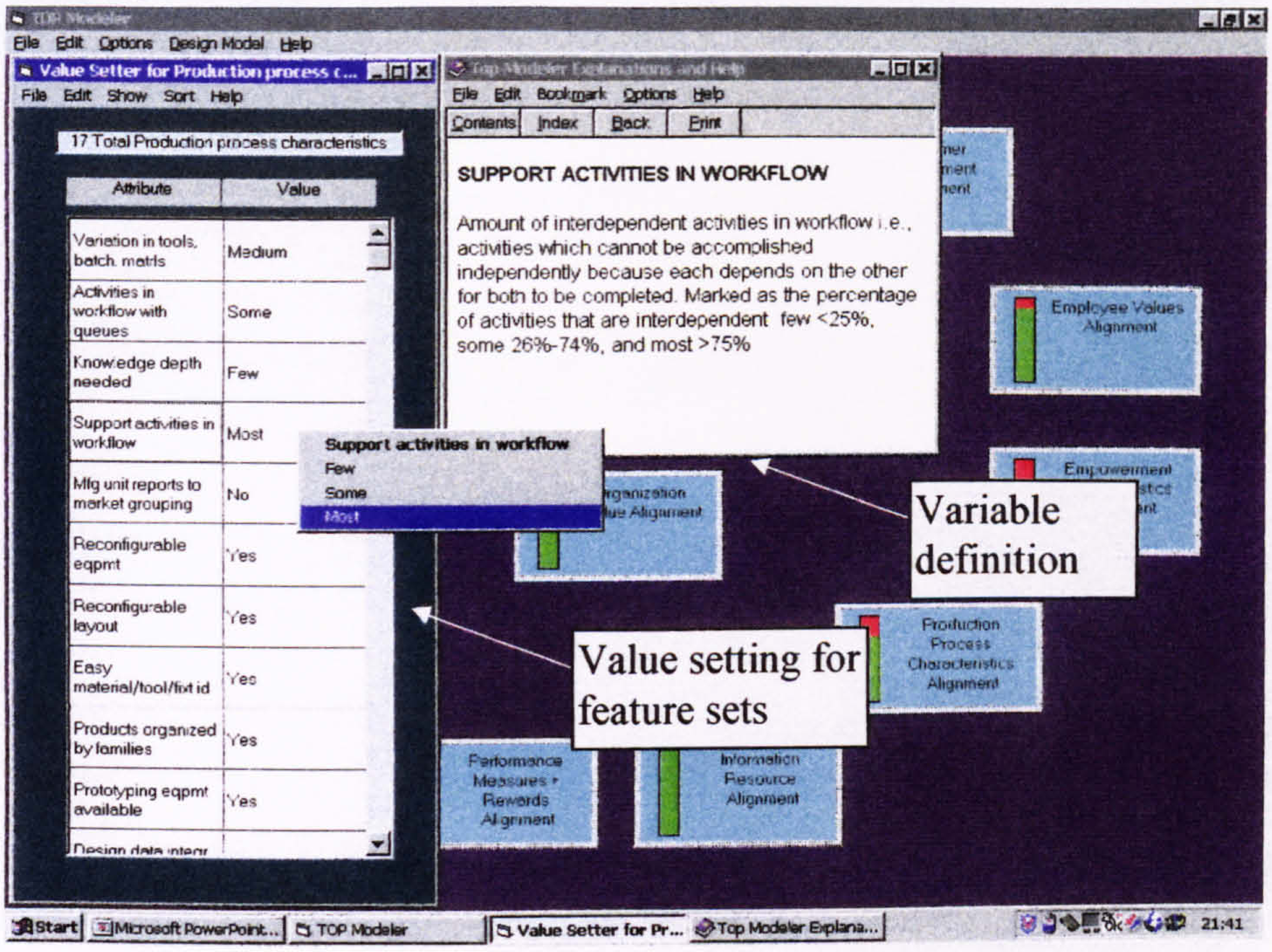


Figure 5-24 Feature Set Value Setting

Value Setting for Each feature Set



5.4.4 Business Objectives Alignment

Following the selection of Process Variance Control Strategies, the subsequent step is to determine if any of the selected strategies conflict with the Business Objectives. The modelling tool provides a simple matrix (see Figure 5-25) comparing an ideal set of values against those selected by the user. Potential conflicts are highlighted.

Having selected appropriate Process Variance Control Strategies and Business Objectives the final Business Strategy, Organisational Values are selected. Organisational Values describe the preferences of management about underlying beliefs concerning how employees (management included) should behave. These values include such behaviours as the degree of collaboration, risk-taking, and continuous improvement expected of employees. Having selected Organisational Values, the design team is able to examine the extent to which the selected Organisational Values conflict with the Business Objectives and Process Variance Control Strategies.

5.4.5 Alignment of Operational Feature Sets

Once all three aspects of the Business Strategy are aligned, it was possible to determine the extent to which the organisation is currently designed to achieve that Business Strategy. This is determined by considering the alignment of the remaining eleven feature sets of the organisation with the Business Strategy. These feature sets are:

- Information Resource,
- Production Process Characteristics,
- Empowerment Characteristics,
- Employee Values,
- Customer Involvement,
- Skill,
- Reporting Structure Characteristics,
- Norms,
- Activities,
- General Technology Characteristics,
- Performance Measures and Rewards.

Each feature set is defined, and relationships between Business Strategies and feature sets displayed in each Matrix. As each organisation or technical feature is entered the matrix is used to determine if providing that feature supports and enhances the Business Strategy. A tool is provided to indicate the degree to which the selected features reflect the ideal attributes given the selected Business Strategy.

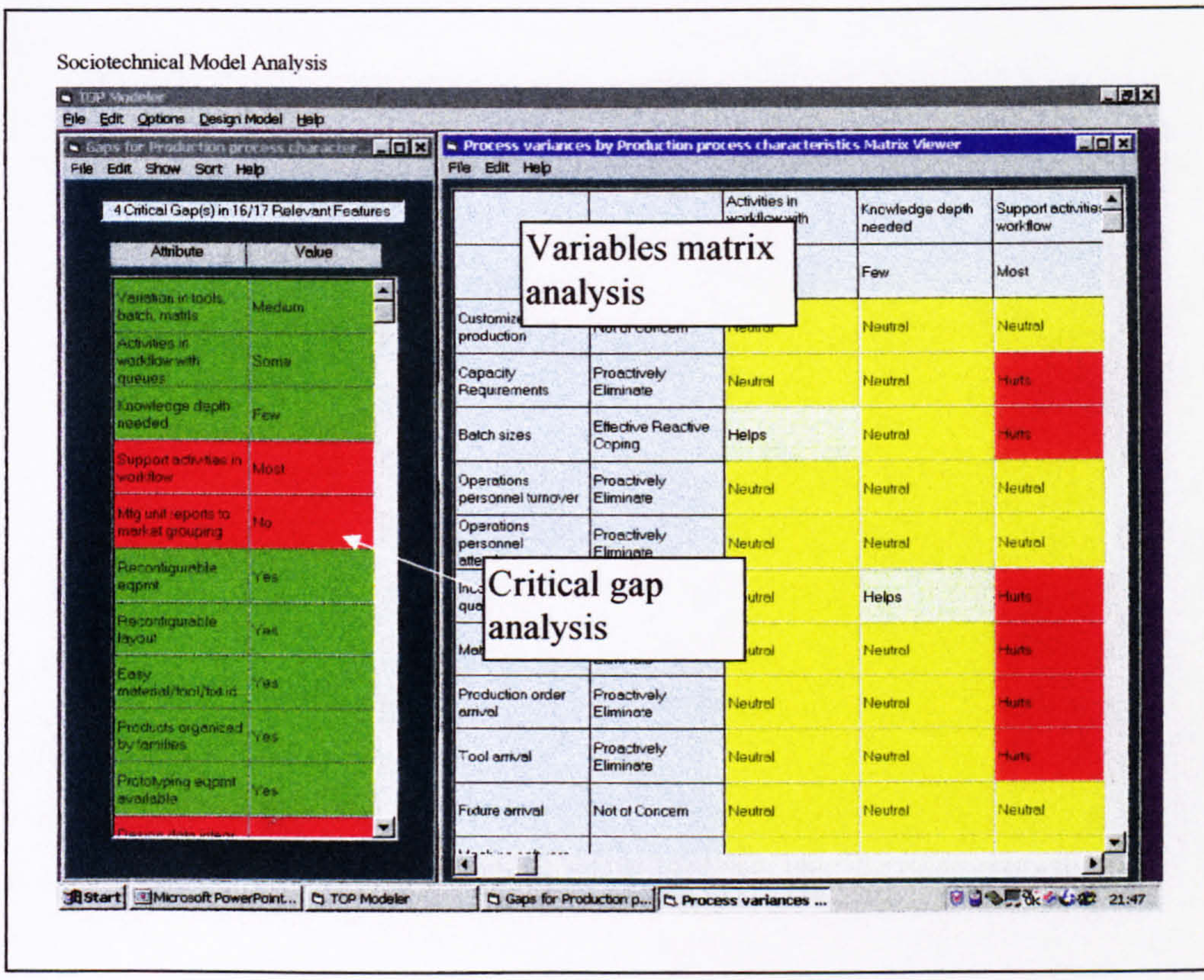
5.4.6 Feature Set Alignment to Ideal

Having completed the *Feature Set* input analysis tools are provided to identify which elements of a particular *Feature Set* have greatest variance from the ideal. The features are listed in priority order, where the number of different business strategies that the feature is affecting determines the priority. The analysis tools assist in the identification of patterns across the feature sets, for example: If the *Skills Feature Set* has a poor rating compared to the *Technology Set*, a reasonable conclusion may be to begin improvements with basic skills and/or to consider those actions that may be taken during the control technology design to reduce the need for specialist skills.

5.4.7 STA Output Variables and Relationships

Completion of the analysis provides an ordered set of variables and relationships, aligned with the strategic, organisational, technological and human resource features of the organisation. This establishes the primary input into the Technical Requirements Analysis stage.

Figure 5-25 TOP Modeller Analysis



5.4.8 Skill Set Identification and Skill Alignment

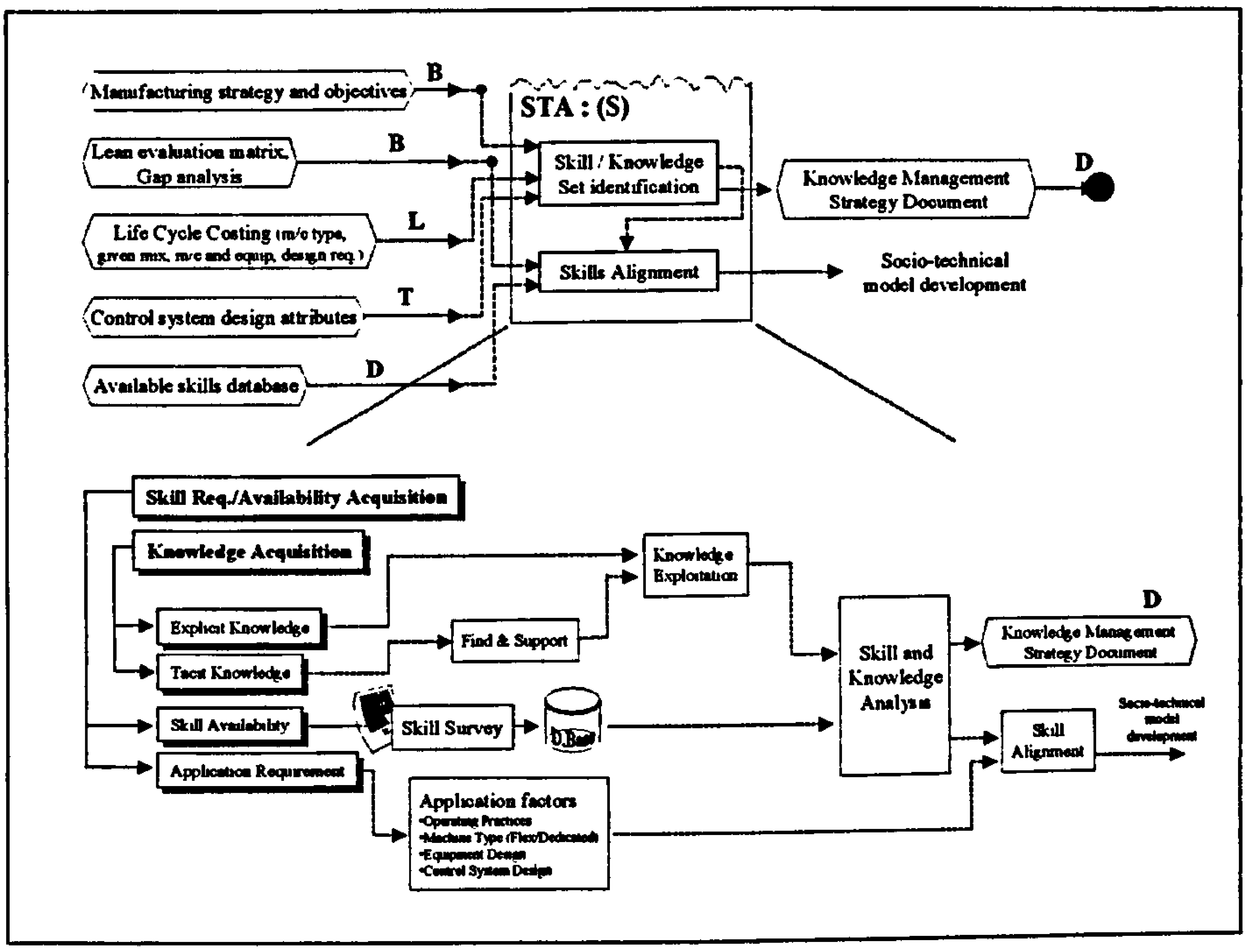
The completion of the Socio-technical model requires an assessment of available skills and their alignment with the proposed business and technical requirements of the design. Additionally the program will require a *knowledge management strategy*; both processes are illustrated in Figure 5-26. There is no single method that enterprises can turn to when looking to improve the efficiency and effectiveness of corporate knowledge and skills however the NGC design philosophy identifies four factors that must be considered in order to realise an effective knowledge and skill management strategy. These are:

Managing explicit knowledge. This means capturing knowledge in documents and making these documents available as needed. The focus is on leveraging and exploiting knowledge that is already available in the enterprise, but which has not been accessible to people who could take advantage of it.

Managing tacit knowledge, This knowledge is not in a system or embedded within a process. Benefit for the organisation is gained by finding people with relevant skills and knowledge and supporting the interactions between them. This includes not only identifying appropriate contacts, but addressing human and technical issues that stop the knowledge moving from the *tacit* to *explicit* zone. Often during a new program an organisation must acquire new knowledge as well as making better use of existing knowledge, this raises new issues. Where possible the knowledge acquisition should be structured to ensure it remains in the *explicit zone*. Each of the areas described contribute to a Skill/Knowledge Analysis finally resulting in a *Knowledge Management Strategy Document* that is used by the Training department to direct the training requirements as the equipment is installed.

The remaining two factors are: *Skill availability database* and *Application skill requirements.* The *'Skill availability database'* is constructed initially by carrying out structured surveys with each member of staff. When the database is populated it is beneficial to keep the records up-dated via automated notification of training completion. The skills profile are analysed and make up one of the two inputs into the *Skill Alignment* process. The second input into the alignment process emanates from a study of the application requirements. Factors such as: operating practices, machine type, equipment design and control system complexity will all need to be considered. As with many other processes in the NGC design framework the application requirement will need to be revisited a number of times before the design is finalised. The output from the skill alignment process is fed to the Socio-technical model described above.

Figure 5-26 Skill Set Identification and Alignment

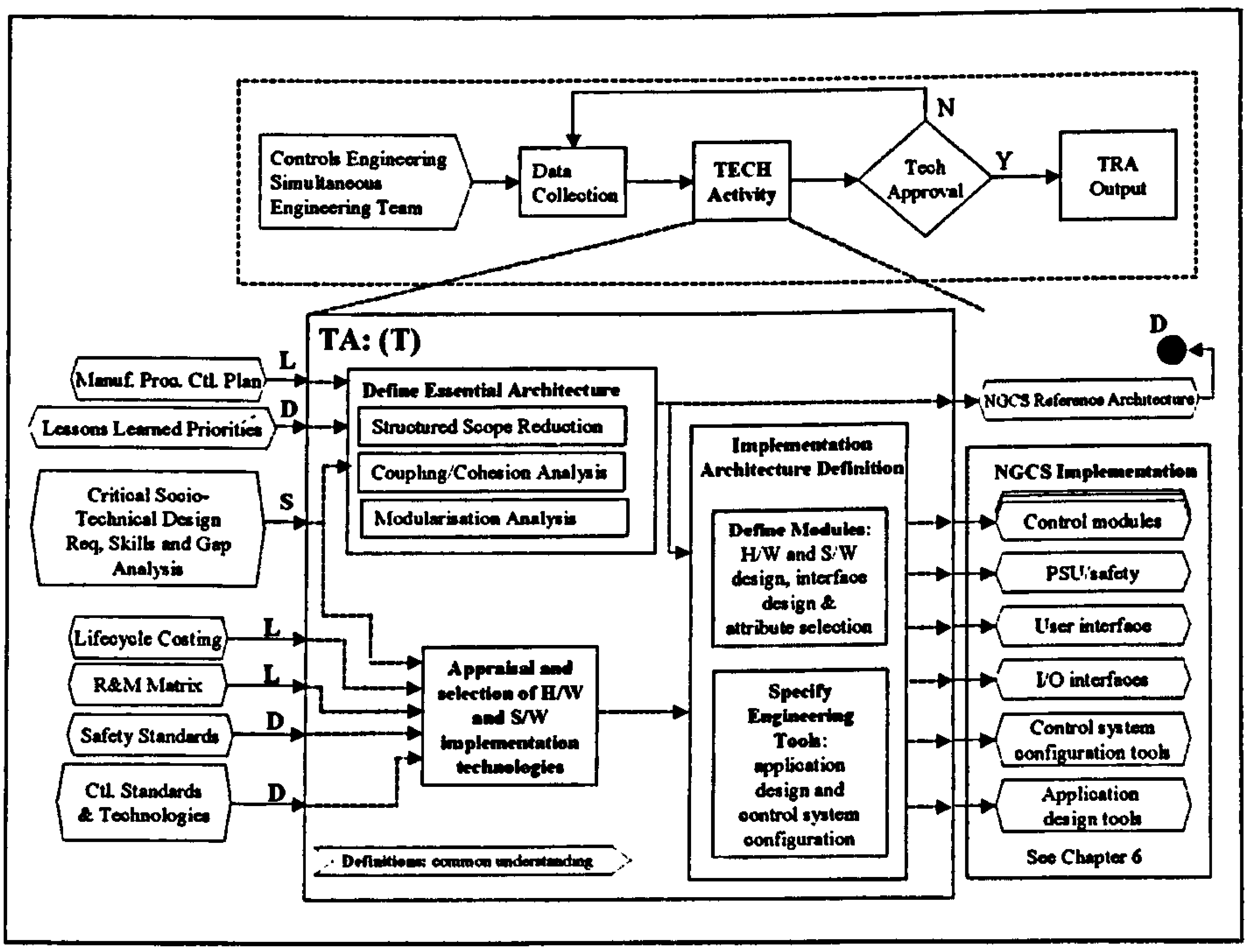


5.5 Technical Requirements Analysis

The Technical Requirements Analysis (TRA) is the final phase of the DRAC environment. An extensive literature survey of TRA application design tools is beyond the scope of this thesis, however, a number of suggested tools are highlighted and applied in the *proof of concept* system shown in Chapter 6. The aim of the TRA is to accept the variables and relationships from the previous stages and by utilizing defined processes and available tools, define a *Reference Architecture* and list of suitable *Hardware and Software Implementation Technologies* .

The NGCS Implementation process is initiated by two parallel activities as shown in Figure 5-27. The two processes are: definition of the *Essential Architecture* and the *Appraisal and selection of hardware and software implementation technologies.*

Figure 5-27 Technical Requirements Analysis



5.5.1 Essential Architecture Definition

The *Essential Architecture* definition fulfils one of the *Solution Principles* identified in Chapter 4 by utilising a process of structured scope management that aims to identify a modular, stable design with inherent structural stability. A representation of the process is shown in Figure 5-28. The *Manufacturing Process Control Plan* input defines the types of machines required and the functionality of each machine. The integration requirements, both between machines and with higher level production and business systems (See Figure 5-10) are defined.

The identified manufacturing applications are ordered into the appropriate *Tier of Architectural Definition*. The scope and application domain is widest at tier 1 and at it's most specific at tier 'n', where 'n' is the tier with the narrowest scope and application domain. In the example shown (Figure 5-28) three tiers are identified, namely a Zone Controller Tier, Machine Controller Tier, and in the lowest tier with the narrowest scope an Automation Controller Tier. Each *tier* requires a number of functional control elements known as *Architectural Units* to form the required functionality, examples being: drive systems, logic control elements and application software. These are in turn made up of *Atomic Units*, the lowest structural element in the process.

At this stage of the process the application domain and related control elements have been decomposed into a highly modular, but impractical state. Therefore the final stage of the *essential architecture analysis* is an examination of the *Architectural Units* by a team of experienced Manufacturing Control Engineers, and the application of coupling and cohesion analysis. This iterative process is illustrated at a high level in Figure 5-28 and in greater detail in Figure 5-29. The level and form of modularity present in the *Reference Architecture* should ensure that the units are as independent as possible, (known as the criterion of coupling), and that each unit carries out a single, problem-related function; (criterion of cohesion); hence the aim is to design systems with low complexity, minimal coupling and maximum cohesion.

Design Coupling measures design quality by analysing the linkages between *architectural units*. Low coupling between units indicates a well-partitioned system, [Budgen 1993]. Practically this is achieved by: eliminating unnecessary relationships, reducing the number of necessary relationships, and finally by easing the tightness of relationships. The fewer the connections between functional units, the less chance that a fault in one module unit will effect the operation or controlled shutdown of an adjacent system. It should also be possible to change or up/downgrade one unit with minimum risk of having to change or modify another. The Drive Module example shown in Figure 5-29 is refined as the modularity analysis progresses. This is shown by the change from a high number of drive modules with an excessive level of dependency to a system with a rationalised modular structure, low number of interconnections and moderate level of dependency.

Design Cohesion is the measure of the strength of functional relatedness of elements within a unit, [Jones 1988], [Budgen 1993]. Each architectural unit within a tier should contain elements that are firmly related to each other. The ideal module is one in which all the components can be considered as being present for one purpose. In general the *Coupling* and *Cohesion* analysis work together, for example, by grouping the drive related input and output functions into the drive controller module, the *Coupling* between this module and the Logic Controller Module decreases and the functional relatedness (*Cohesion*) increases.

Figure 5-28 Essential Architecture Definition

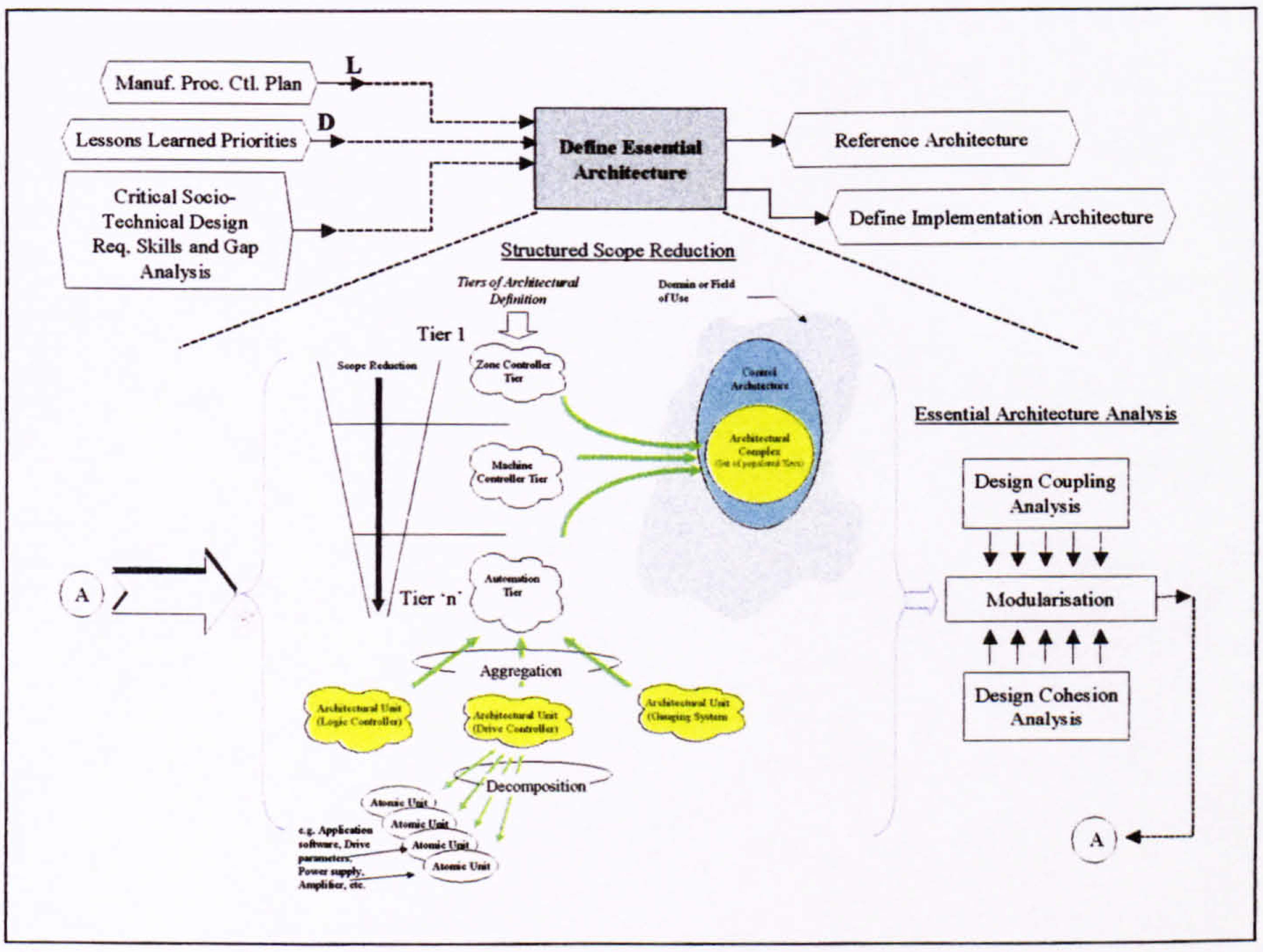
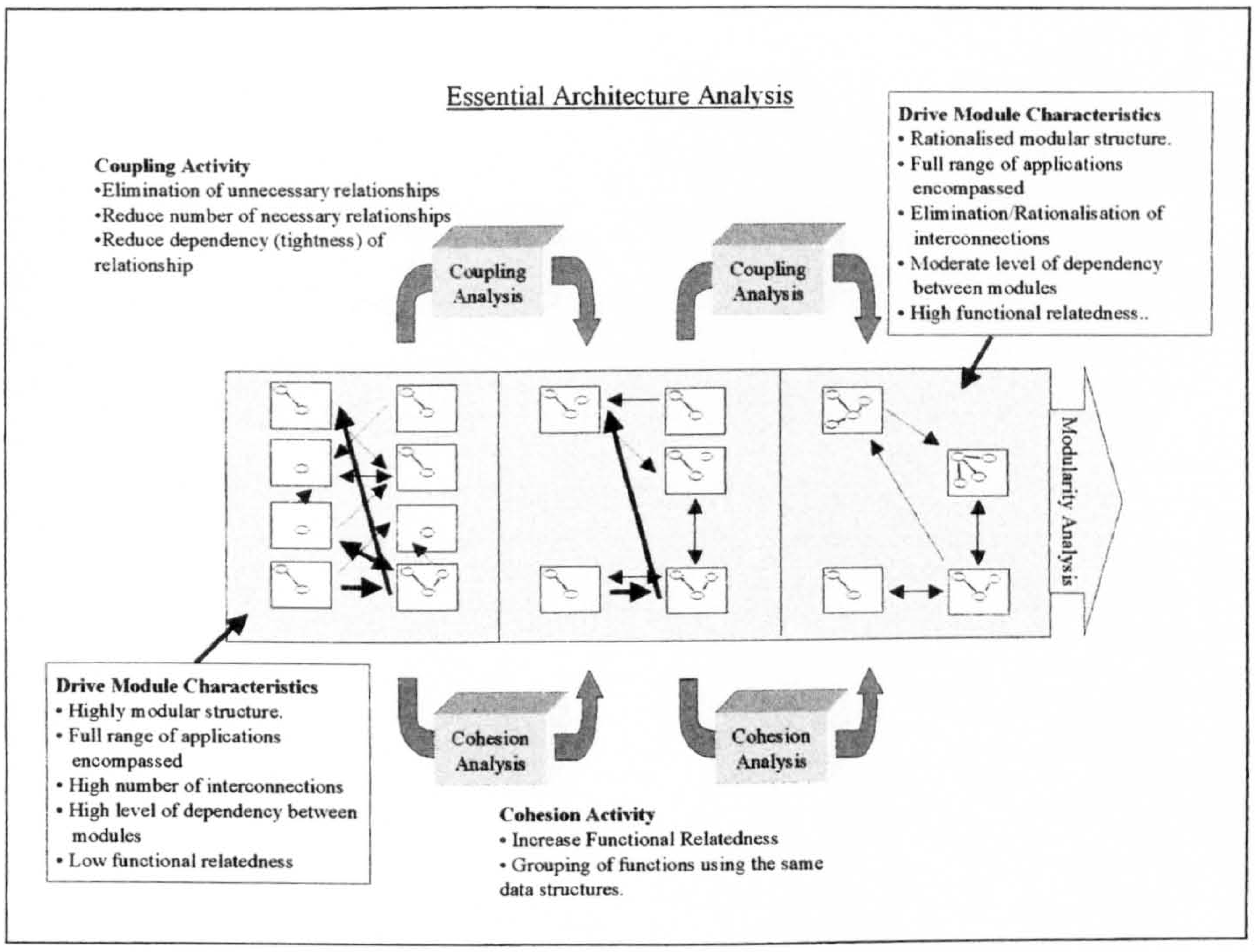


Figure 5-29 Essential Architecture Analysis



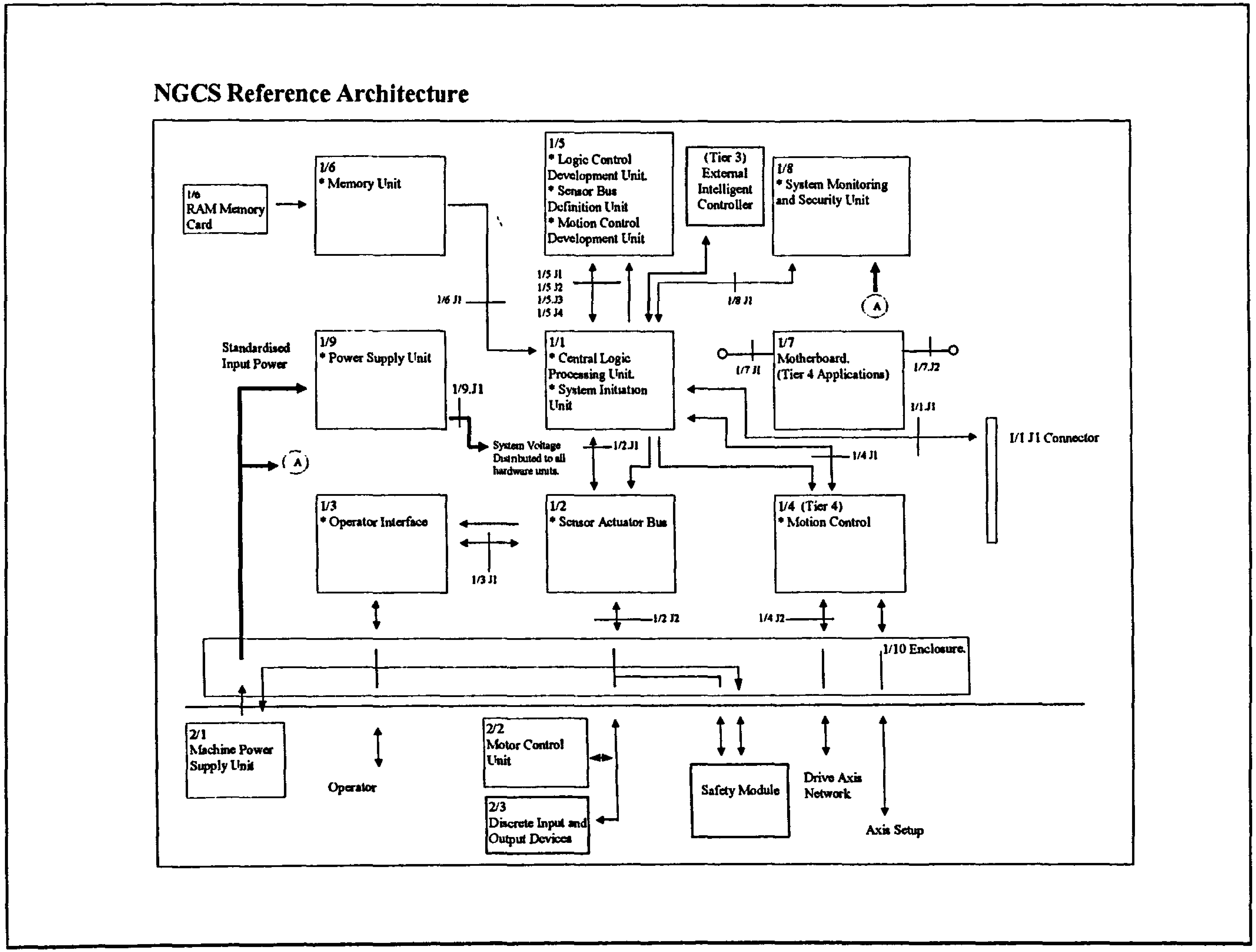
5.5.2 NGCS Reference Architecture

The output from the *Essential Architectural Definition* is the *NGCS Reference Architecture (RA)* as illustrated in Figure 5-30. The *RA* is implementation independent and aims to provide the optimum design in terms of structure, modularity and reconfigurability. Consistent with other parts of the process, standardised notation and definitions are used to identify the *architectural units* and their associated interface. The notation for an interface is unit / number.interface number, (e.g. 1/4.J.1). Like the *architectural unit*, the interface may be hardware, software or a combination of both. For example Module 1/5 contains the logic development environment and as such is entirely software based. The Power Supply module (2/1) and Motherboard (1/7) are hardware based and the remaining modules a mixture of both hardware and software functionality. A summary of each sub-system unit and its primary interface requirements are presented in table 5-7.

Table 5-7 Architectural Units and Primary Interfaces

Unit or Interface	Description
1/1 Unit	*Central Logic Processing Unit*
1/1 Interface Requirements	1/1.J1: Sub-system compatibility with external interface connections.
1/1 Unit	*Sensor / Actuator Unit*
1/2 Interface Requirements	1/2.J1: Defines the address area assignment of the I/O port. 1/2.J2: Sets the mechanical connection between the unit and the enclosure.
1/3 Unit	*Low Level Operator Interface Unit*
1/3 Interface Requirements:	1/3.J1: Interface via sensor actuator bus. Interface defined by relevant international body.
1/4 Unit	*Motion Control Unit*
1/4 Interface Requirements:	1/4.J1: Defines the address area assignment of the I/O port and function of individual registers. 1/4.J2: Interface to Drive Systems. Interface defined by relevant international body.
1/5 Unit	*Logic Control Development Unit* *Sensor Actuator Bus Definition Unit* *Motion Control Development Unit*
1/5 Interface Requirements	1/5.J1: Software Interface to Sensor Actuator Unit. 1/5.J2: Software Interface to Motion Control Unit. 1/5.J3: Software Interface to Central Logic processing Unit. 1/5.J4: Software Interface to System Monitoring and Security Unit.
1/6 Unit	*Memory Unit*
1/6 Interface Requirements	1/6 J1 Interface with Central Logic Processing Unit during system initialisation.
1/7 Unit	*Motherboard Unit*
1/7 Interface Requirements	1/7 J1 Mechanical and Electrical Interface to all hardware units. 1/7 J2 Mechanical Interface to Enclosure.
1/8 Unit	*1/8 System Monitoring and Security Unit*
1/8 Interface Requirements	1/8.J1: Defines the address area assignment and CPU interrupt for power and scan failure.
1/9 Unit	*1/9 Power Supply Unit*
1/9 Interface Requirements	1/9 J1 Internal Power Interface, distribution to all hardware units.
2/1 Unit	*2/1 Machine Power Supply Unit*
2/2 Unit	*2/2 Motor Control Unit*
2/3 Unit	*2/3 Discrete Input and Output Interface/Devices*

Figure 5-30 NGCS Reference Architecture

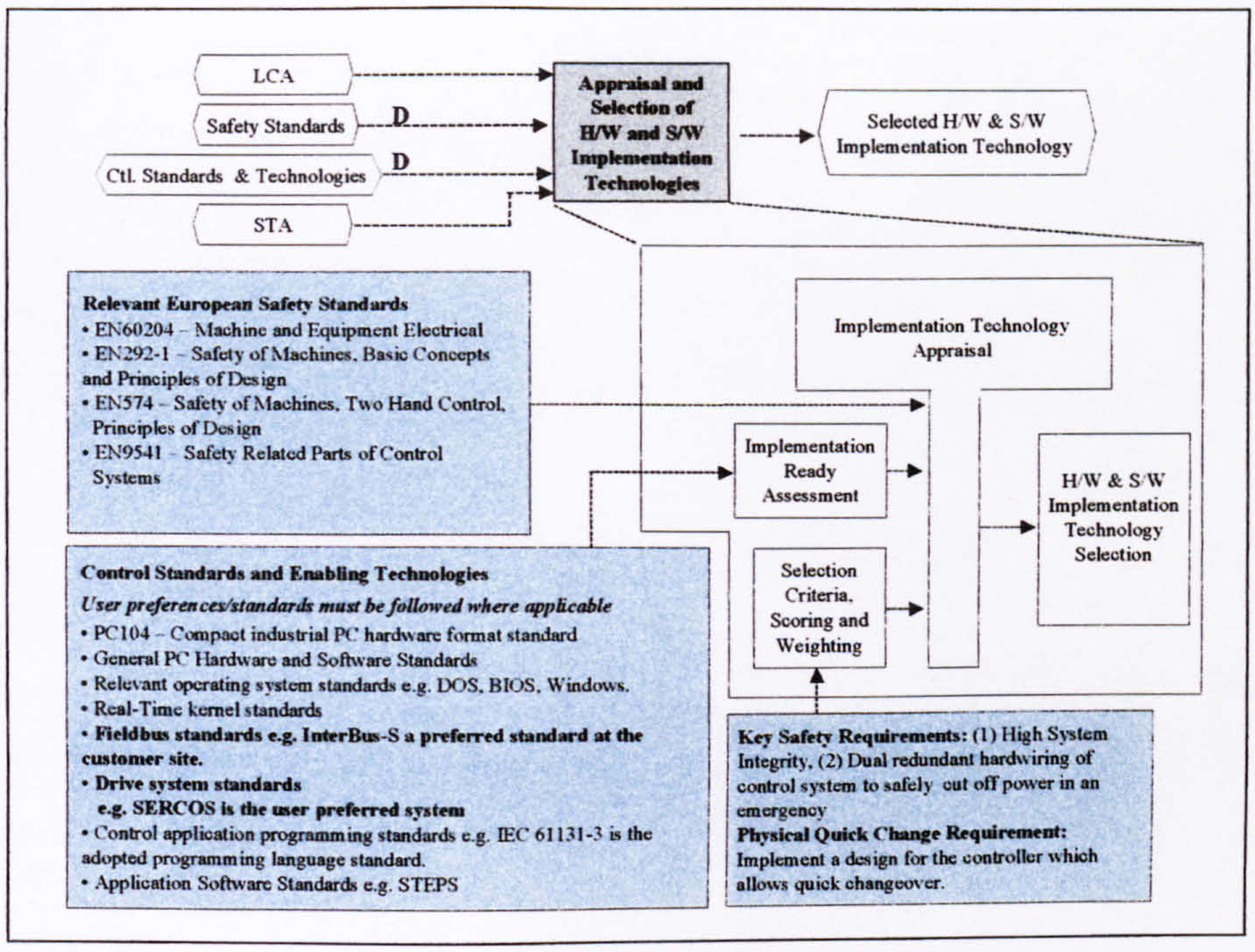


5.5.3 Appraisal and Selection of Hardware and Software Technology

The process associated with the *Appraisal and Selection of Hardware and Software Implementation Technology* is illustrated in Figure 5-31. The first of three input groups encompasses safety related attributes requiring high integrity systems often with dual channel operation and automatic progressive failure detection. Examples include: European standards that cover the design of Two Hand Control (EN574), Safety of Machines (EN292-1) and Safety Related Parts of Control Systems (EN9541). Necessarily these standards provide limited scope for innovation or user preference.

In contrast the second group of inputs include *Control Standards and Enabling Technologies* where user requirements and preferences play an important role in defining the technology used. Examples include PC Hardware format (PC104), interface software, serial bus standards and application software. In this category often new and in some cases untried technologies will be considered; therefore the associated risks and benefits must be taken into account. A discrete process associated with this group determines the *implementation readiness* of the technology. The judgement of a particular technology's readiness must be based on predefined criteria as determined by the business environment, risk culture within the organisation and time to deployment. It should be taken into account that the level of risk that the organisation is willing to bear will change from time to time due to economic and personnel changes. The final group of inputs from the BEA, LCA and STA environments set and define the *Selection Criteria, Scoring and Weighting* of the selected hardware and software options. All three groups pass through an appraisal process that aims to select the most appropriate technologies.

Figure 5-31 Appraisal and Selection of Implementation Technologies



Two *zones of influence* are shown in Figure 5-32. Although both *zones* are provided with *critical design requirements* from the same source (BEA, LCA and STA environments) it is evident that the upper zone processes the architectural requirements of the design. This *zone* is referred to as the *zone of architectural* influence, creating the *Reference Architecture* as an output. In contrast the lower *zone* focuses on technologies and standards. This technological focus provides as an output, a list of selected hardware and software technology. The author refers to this area as the *Zone of Technological Influence*.

The practical realisation of control modules, application design tools and associated interfaces must combine the attributes of both *zones* to produce an NGCS implementation. Each applied component will contain attributes from both the architectural and technological zone of influence.

A number of practical examples of this concept are given in Chapter 6 however to illustrate the concept an example is given in Figure 5-33. The proof of concept system incorporates an SRAM memory module (that stores all the application data) and a software initiation module designed to automatically distribute the application software to intelligent modules remote from the main central logic-processing unit. The architectural input requirements (intelligent sub modules, multi-skilled operation, high system availability and system agility) are processed by the *Essential Architecture Definition.* The output is represented in the Reference Architecture by two units: a memory module (1/6) and a system initiation module (1/1).

The technological influences include: memory size, read/write technology, form and cost. The software functionality inputs are: programming language, interface (if any) with the operator and configuration tools. These design requirements are processed by the *Hardware and Software appraisal* resulting in the selection of an SRAM memory card with a PCMCIA interface. The analysis identified that the multi-skilled operator would not interface with the system configuration therefore to increase the response time of the download process the initiation software was written in a high level language and embedded into firmware contained within the central logic processing unit 1/1. The Architectural and technological influences are combined in the *Implementation Architecture definition.*

If the Business, Life Cycle or Socio-technical requirements had been different the practical implementation would have taken a different form. For example, if the multi-skilled operator needed to reconfigure the system; a screen on the operator interface would be required increasing cost and development time. Equally if the system was never going to be reconfigured and there was no requirement for intelligent sub modules the system initialisation module 1/1 could be eliminated and the memory loaded on to standard EPROM's saving cost and system complexity.

Figure 5-32 Architectural and Technological Zones of Influence

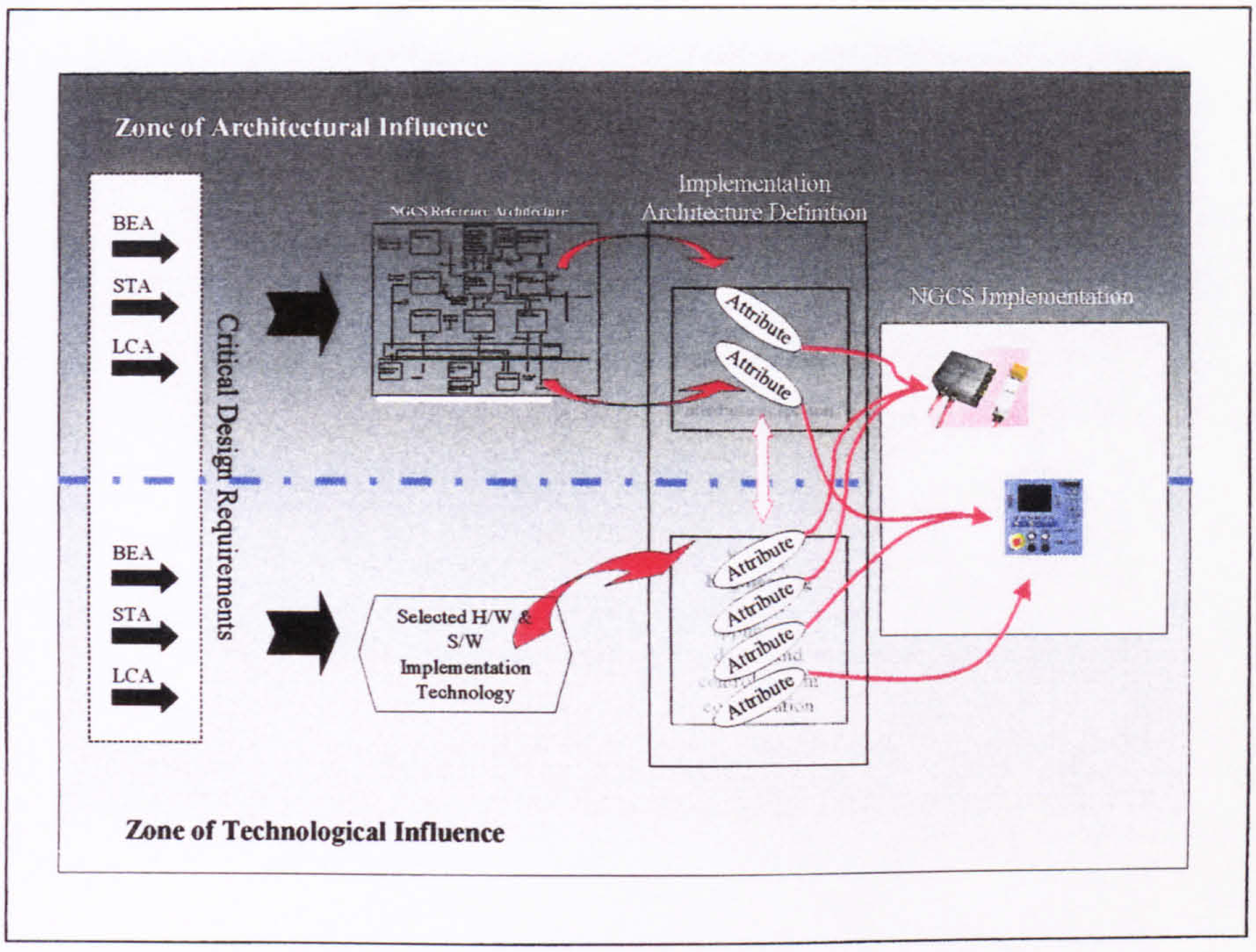
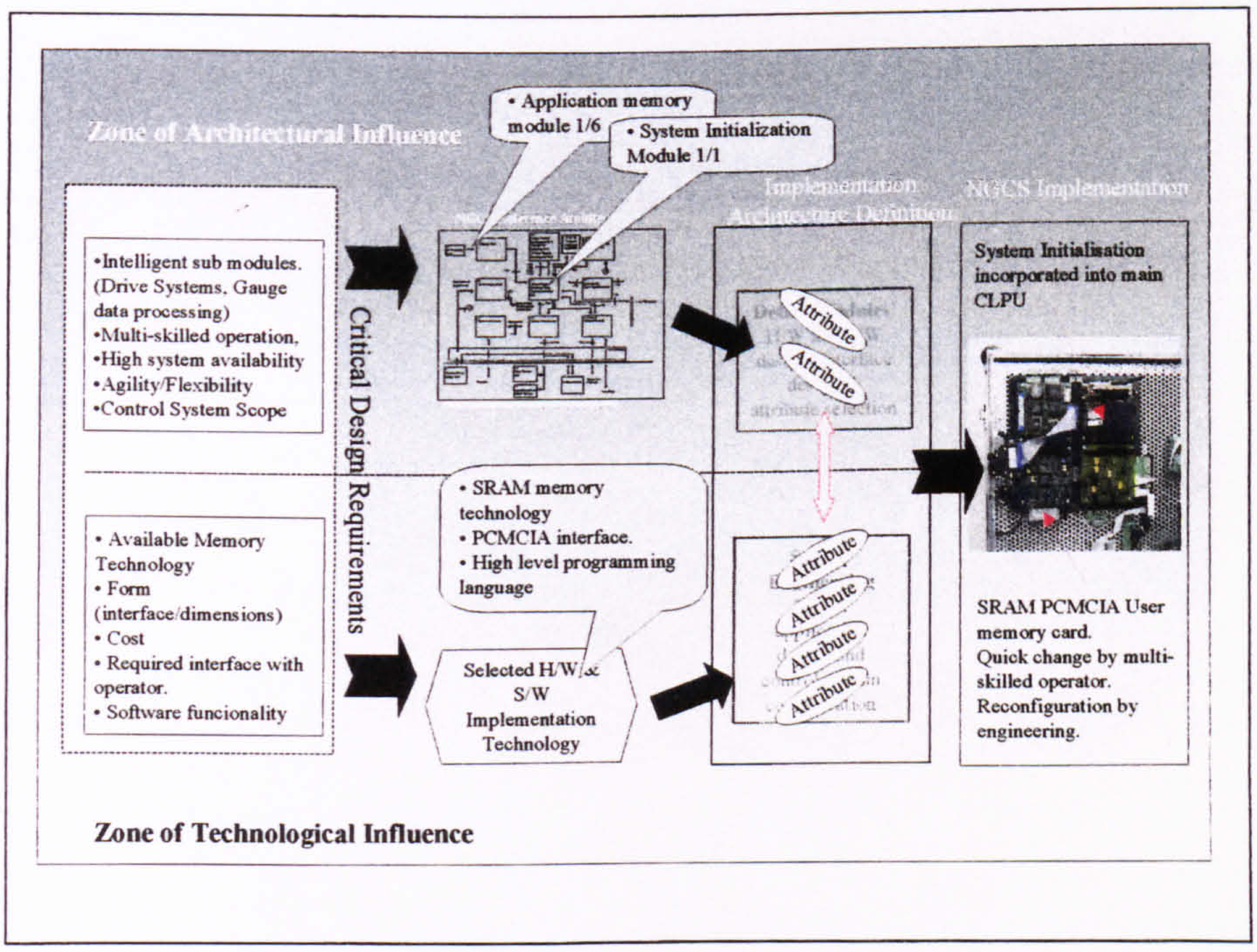


Figure 5-33 Practical Example of Module Development.



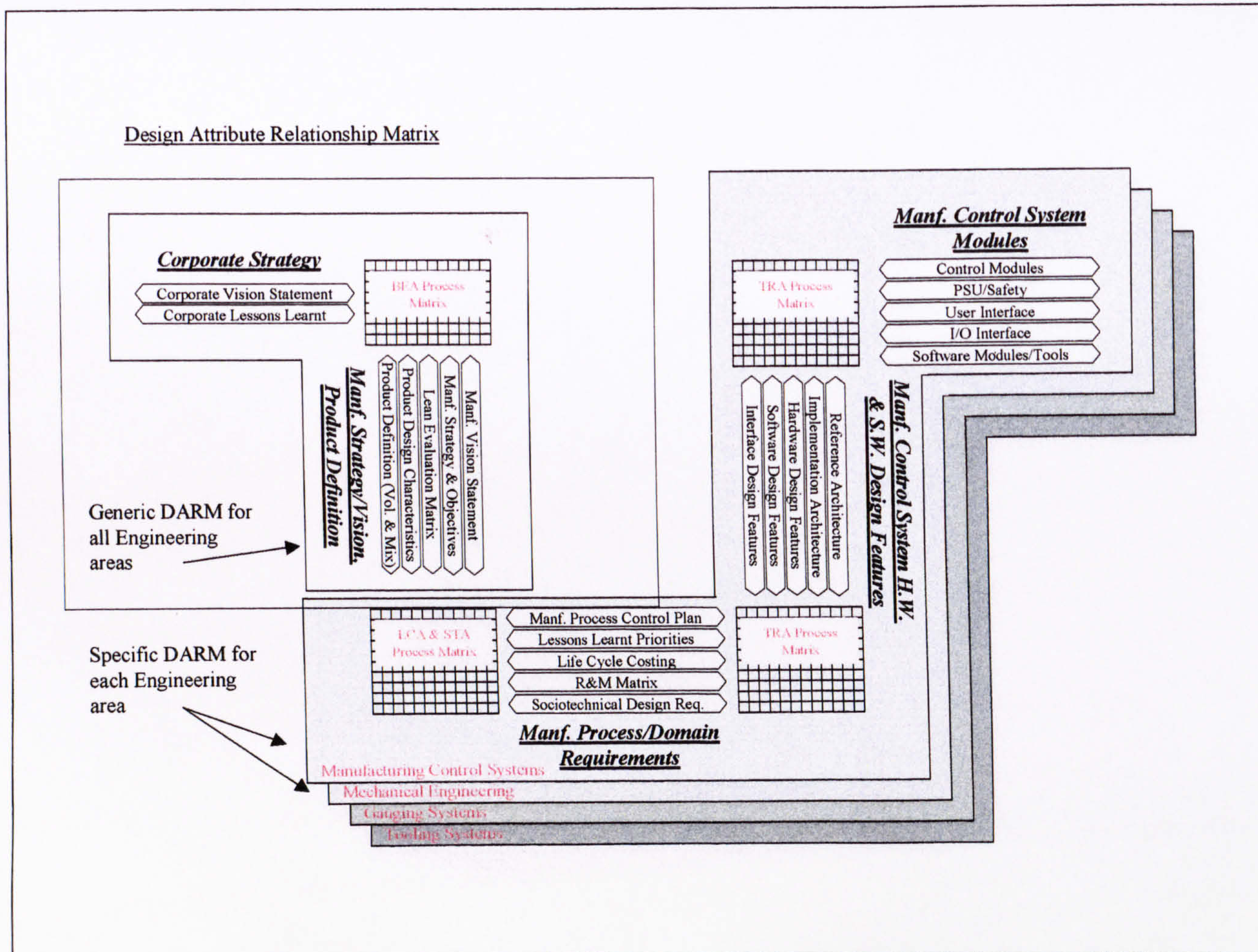
5.6 Design Attribute Relationship Matrix (DARM)

The Business, Lifecycle Cost, Socio-technical and Technical phases generate a high number of complex requirements and interdependencies. Throughout the four phases presented in this chapter an implicit decision making process is continuously being made that violating one ideal relationship is less damaging than violating others. The designer must recognise that the inevitable compromises found in practical designs may surface as a flaw in the completed design and hence documentation of the violations provides a rationale for the compromises.

To assist the designer the decisions made during each of the phases are captured and linked together in the form of interconnecting matrixes. This is referred to as a Design Attribute Relationship Matrix (DARM) an example of which is shown in Figure 5-34. The aim of the interconnecting matrixes is to highlight to the various stakeholders in the design process the relationship between the key business, lifecycle, socio-technical and technical design factors, and promote a method of forward and backward propagation between them. It is important that the DARM is used not only to record initial design decisions, but also to assess the potential impact of requested changes to the system.

The Corporate Strategy and Vision/Strategy/Product Definition sections of the DARM (contained within the first two matrixes) are common to all the manufacturing engineering areas. Moving through the matrix sets, the detail increases therefore after the second matrix a specific DARM is required for each engineering discipline (e.g. Control Systems, Mechanical Engineering, Gauging and Tooling Systems). A worked example tracing individual design features is presented in Chapter 6.

Figure 5-34 Design Attribute Relationship Matrix



5.7 Summary

In this chapter a detailed description of the NGCS Conceptual Design Framework is provided. Four distinct phases are identified namely: Business Environment Analysis, Lifecycle Analysis, Sociotechnical Analysis and finally the Technical Requirements Analysis. The four phases are bound together using a mapping process in the form of a Design Attribute Relationship Matrix (DARM).

The Business Environment analysis identifies the corporate and *end product* requirements. This in turn allows definition of the strategic manufacturing direction. Four activities are described namely: Vision Document development, End Product complexity mapping, Manufacturing Programme Strategy definition and Product Design.

The Life Cycle phase describes the activity required to initiate the manufacturing dimensional and process flow planning. The importance of retaining and collecting new knowledge within a global organisation is highlighted and a method to prioritise knowledge described. A model to judge system *Life Cycle* cost is introduced. The final step of the Life Cycle Cost phase establishes Reliability and Maintainability (R&M) objectives, requirements and design objectives. The integration of R&M requirements into the overall process is discussed and the use of data to design reliable and easily maintained equipment.

The Socio-technical Design Phase identifies a design approach that promotes the view that organisational systems function effectively and proactively when the technical, organisational and human elements are compatible and integrated with each other. This chapter provides a method to align strategic, organisational design, and human resource variables identified in the domain analysis, to order and weight the variables, to define relationships between the variables, and to identify and prioritise features that need to be addressed in the technical design analysis. The STA environment provides a process to assess the available skills in the manufacturing environment and their alignment with the proposed business and technical requirements of the design.

The final phase of the DRAC environment is the Technical Requirements Analysis (TRA). The TRA accepts the variables and relationships from the previous stages and processes them through two zones of influence. The *Architectural Zone of Influence* provides as an output an NGCS *Reference Architecture.* The architecture is subjected to analysis and testing to ensure the structure is implementation independent and provides the optimum design in terms of structure, modularity and reconfigurability. The *Technological Zone of Influence* processes the critical design requirements and matches them to available technology. The resultant output provides a catalogue of suitable hardware and software implementation technologies.

Finally the chapter concludes by describing a *Design Attribute Relationship Matrix* which aims to bind the four phases together by highlighting to the various stakeholders in the design process: a/ the relationship between the key business, lifecycle, socio-technical and technical design factors and, b/ promotes a method of forward and backward propagation between them.

The next chapter applies the NGCS Conceptual Framework, initially to a *proof of concept* system and subsequently to an engine assembly line. The implementation is discussed in some detail, focusing on design attributes that differ from conventional manufacturing control system applications.

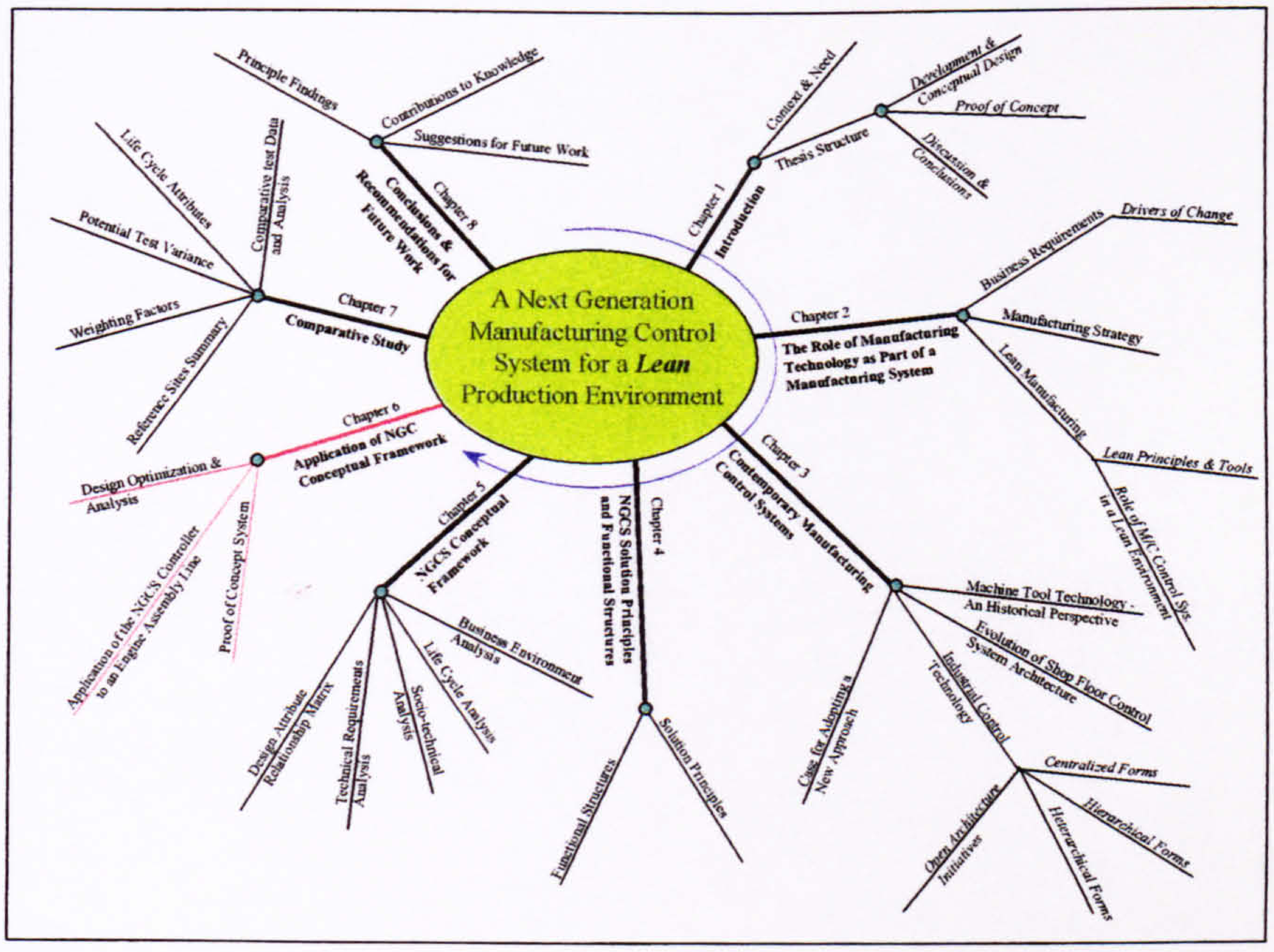
REFERENCES

[Budgen 1993] D. Budgen; Software Design, Addison-Wesley Publishing Company, 1993.

[Jones 1988] M. Jones; The Practical Guide to Structured System Design, Prentice-Hall International Editions. 1988.

CHAPTER 6

APPLICATION OF THE NGCS CONCEPTUAL FRAMEWORK



6. Application of the NGCS Conceptual Framework

6.1 Introduction

Chapter 5 explained in detail each stage of the DRAC environment. The aim of this Chapter is to describe the design implementation and *Proof of Concept System* with a particular focus on design features that differ from contemporary control systems.

The second part of the chapter describes Simultaneous Engineering led by the author with the aim of realising the NGCS design principles on a new high volume assembly line at Ford Motor Company's Dagenham Engine Plant. The chapter begins with a brief resume of the facility and the background that led to the NGCS framework being selected. The Simultaneous Engineering method and structure is outlined and each major application tier is discussed. The proof of concept design is re-examined in light of the practical application and new design features are identified and discussed. In the final section of the chapter the design of the new control system is evaluated and the results critiqued against a similar contemporary assembly line control system.

6.2 Proof of Concept System

To enable the development of a *Proof of Concept System* (PCS) a Structured Scope Reduction for an Engine Assembly Control System was documented (see Figure 6-1). Six tiers of definition are identified; the scope and application domain is widest at tier 1 and at its most specific in tier 6. The scope narrows sufficiently in tier 3 to identify specific 'architectural units'. Four specific application tiers are identified, namely the: 'Zone Controller' tier, 'Complex Machine Assembly' tier, 'Elementary Machine Assembly' tier and finally the 'Transport System' tier. The PCS presented represents a typical machine controller system and models all the major areas of control system applications seen in an engine assembly system.

Three different strategies were employed to realise the component parts, namely, identification of:

- design attributes that can, (through careful selection) be realised using existing products.
- features that can be achieved by reconfiguration and minor modification of existing products,
- requirement *gaps* that will require significant development resource.

Table 6-1 identifies the course of action taken to realise the each NGCS feature in the *proof of concept system*. Each area that differs from conventional control system is described in the following sections. The physical realisation of the Proof of Concept system is shown in Table 6-1.

Figure 6-1 Structured Scope Reduction - Engine Assembly Line

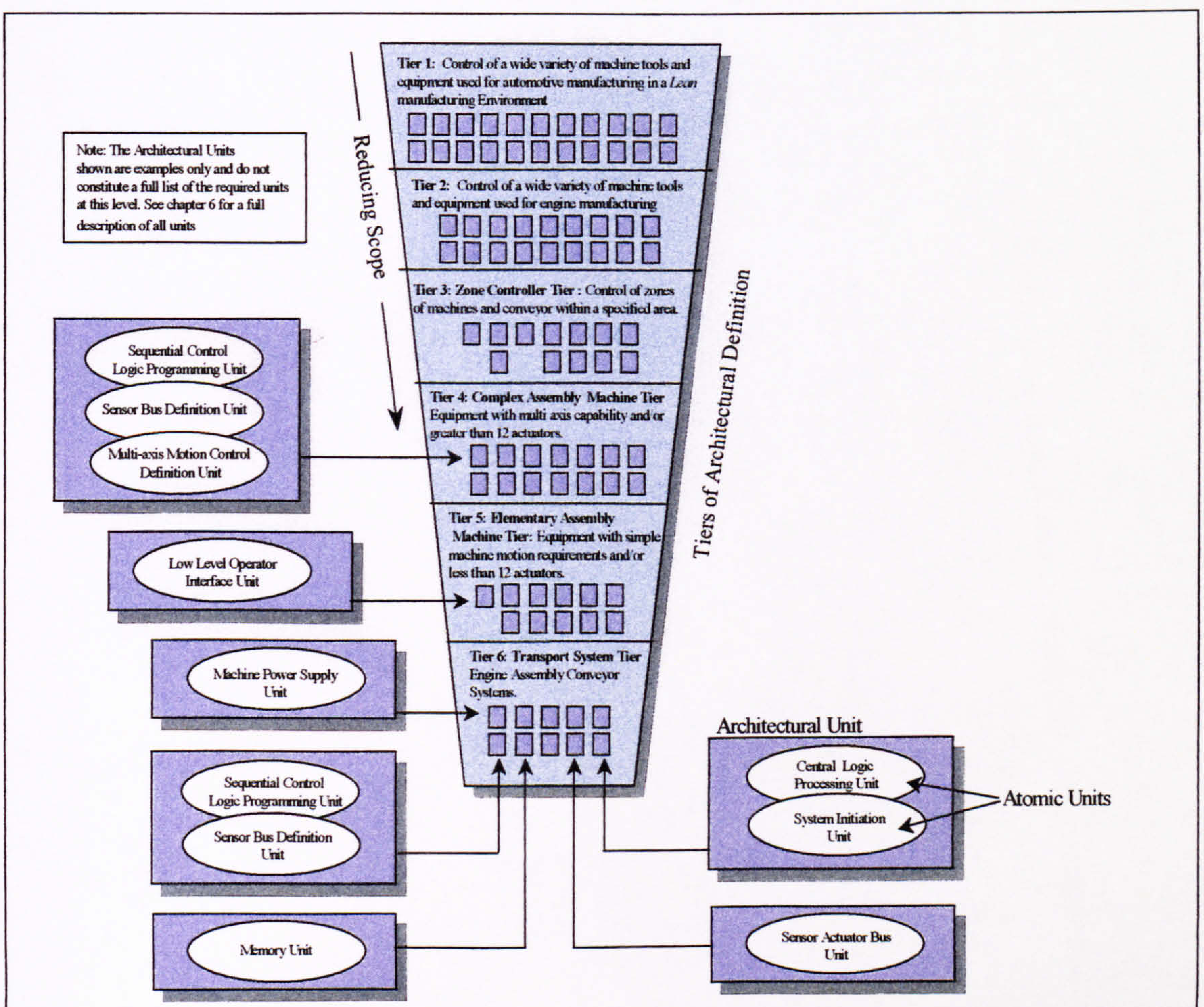
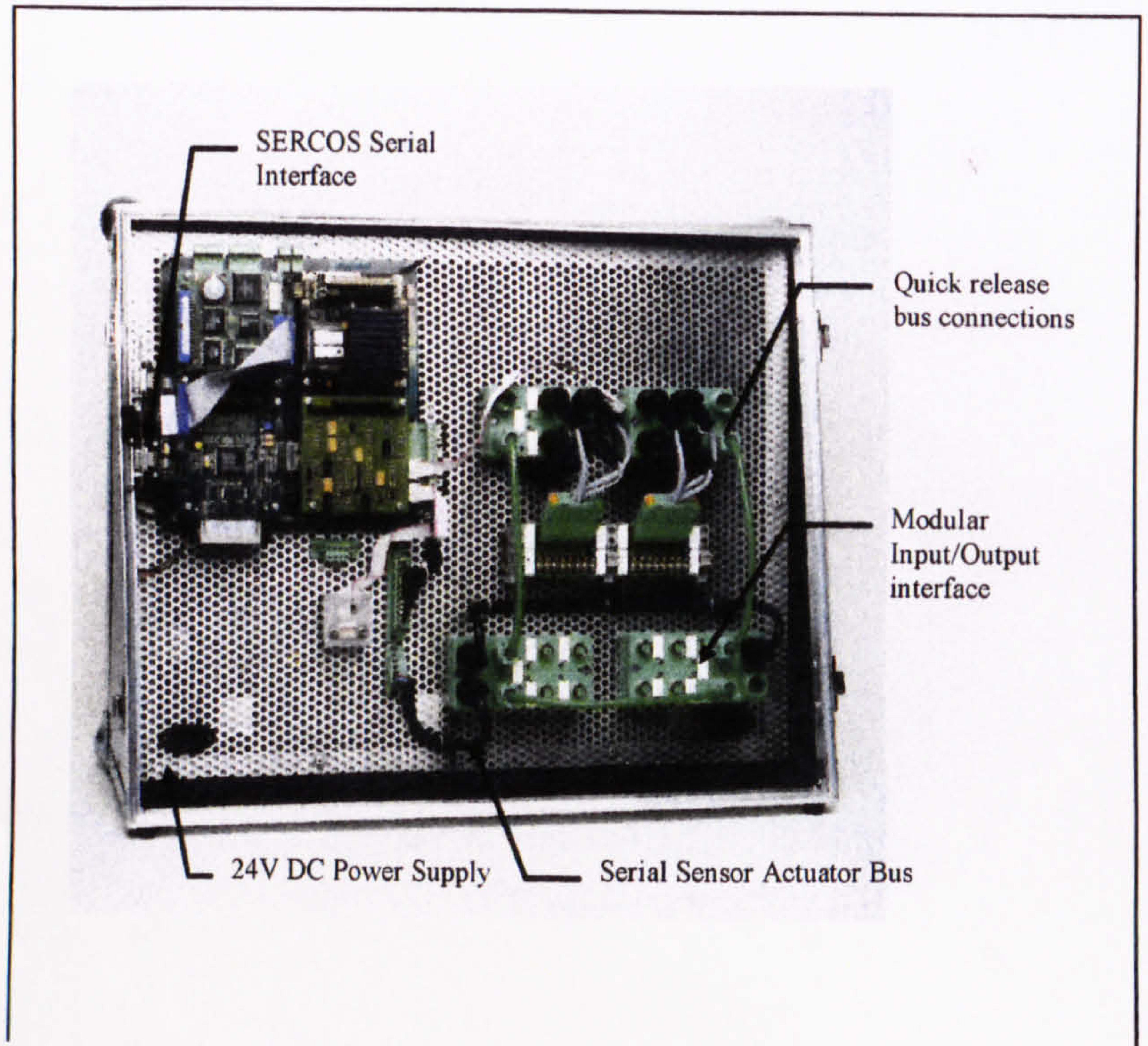
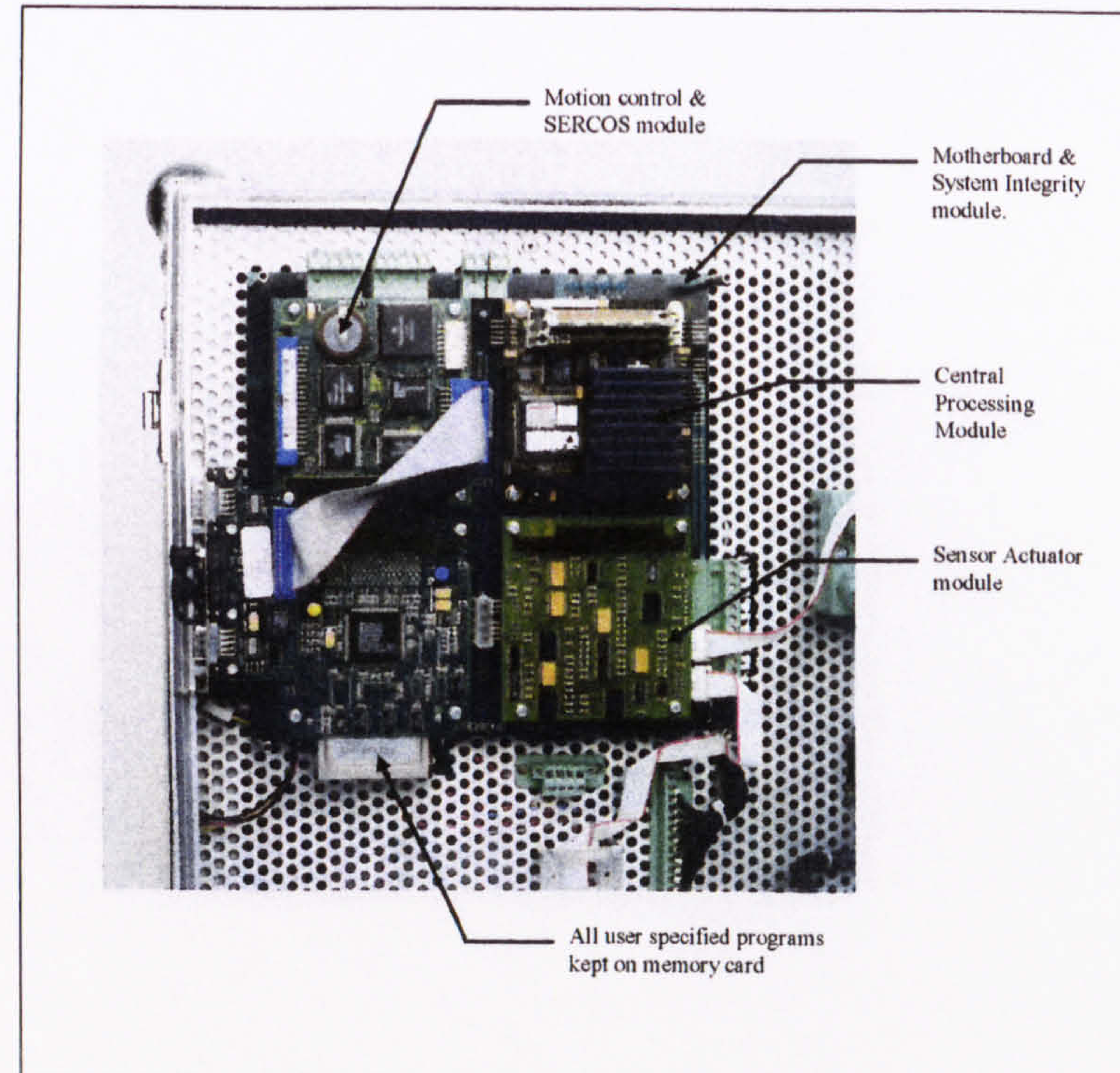


Table 6-1 NGCS Design Attribute Source

NGCS Design Feature	Realised via selection	Realised via configuration/ reconfiguration	'Gaps' requiring further development	Notes
Architectural Units Supporting Tiers of Definition	x	x	x	
Quick release systems	x		x	• Mechanical design for multi-skilled operator. • Not all required systems available in quick release form.
Open architecture system	x			
Standard Voltage and Frequency interface	x			• Standard 24v DC
Supporting hardware			x	• Machine Power Supply • Motor Controller Unit • Servo Axis Controller
Serial bus systems	x			• InterBus
Standard unit interfaces		x		
Compact robust controller hardware	x			• PC104
Modularization		x		
Automatic Software Distribution		x		• Design of batch files
Integrated Software Environment			x	

Figure 6-2 Proof of Concept Design Realisation





6.2.1 Machine Mounted Quick Release System

Machine mounted units designed with *quick release* connection systems facilitate a number of NGCS design requirements including:

- maintenance by multi-skilled operators,
- high equipment availability,
- reduced lead time and cost of machine tools,
- reduced reconfiguration time.

Due to the nature of the proof of concept system few of the principles are realised at this stage.

Ideally, the units are designed to mount directly to the machine structure rather than a traditional control enclosure. The primary reason for this guideline is to aid the multi-skilled maintenance of the units, however, other less obvious reasons exist, namely:

- mounting external to a control enclosure will promote the idea that the control units are *machine function units* in much the same way as a motor or sensor, and as such remove any preconceived ideas regarding traditional labour demarcation[23],
- elimination of the control enclosure reduces machine size and allows the process to be more easily viewed.
- the use of *keyed* connectors eliminates the possibility of incorrect connections.

The concept of *quick release* connection extends to the serial bus medium, the input and output blocks and the connection to the sensors and actuators. The serial bus system selected by the author for the proof of concept system achieved this requirement by using an insulation deformation system.

6.2.2 Implementation of NGCS using Open Architecture Hardware Format

There has been much discussion about the suitability of the IBM Personal Computer platform for industrial control systems [OMAC 1994],[Harbers 1996], [Gyorki 1996]. Over the past decade however, the P.C. architecture has become an accepted platform for far more than desktop computing applications [PC104]. PC's are used as controllers within vending machines, ATM machines, petrol pumps, communication devices and medical equipment to

[23] Currently within most Automotive plants only authorized (electrical) persons are allowed to enter a control enclosure

name a few examples. PCs are now widely available packaged in a variety of forms suitable for most shopfloor environments and real-time control software is available for a range of applications.

Control system designers can substantially reduce development cost, risk, and time by standardising hardware around the broadly supported PC architecture,. This results in faster *time to market* helping manufacturers to meet critical market windows with timely product introduction. Another important advantage is that its widely available hardware and software are significantly more economical than traditional bus architectures such as VME and Multibus, [PC104]. PC's are capable of very high performance, with the advent of PCI bus technology, the standard PC hardware architecture can be used to cover the full spectrum of real time and monitoring applications identified in the Architectural Tiers. A controller may be simply a low end PC running a single task or may require several coprocessor cards with multiple operating systems and special purpose sub-systems.

The author believes that a major factor in the more widespread use of PC based control has been the emergence of control network standards for motion and I/O. This has removed the problem of providing direct connection to input and output devices, a traditional strength of the PLC. Typically network connections are available for most devices allowing network interfaces manage the connection to the physical environment.

The standard PC form factor is bulky and requires expensive mechanical systems to ensure a robust system. Some of the Architectural Specification requirements are in practice difficult to achieve with the standard PC bus form factor (12.4" x 4.8") and its associated card cages and backplanes. The use of the standard format would lead to the new controller to be larger than equivalent PLC systems, particularly on tier 5 and 6 applications.

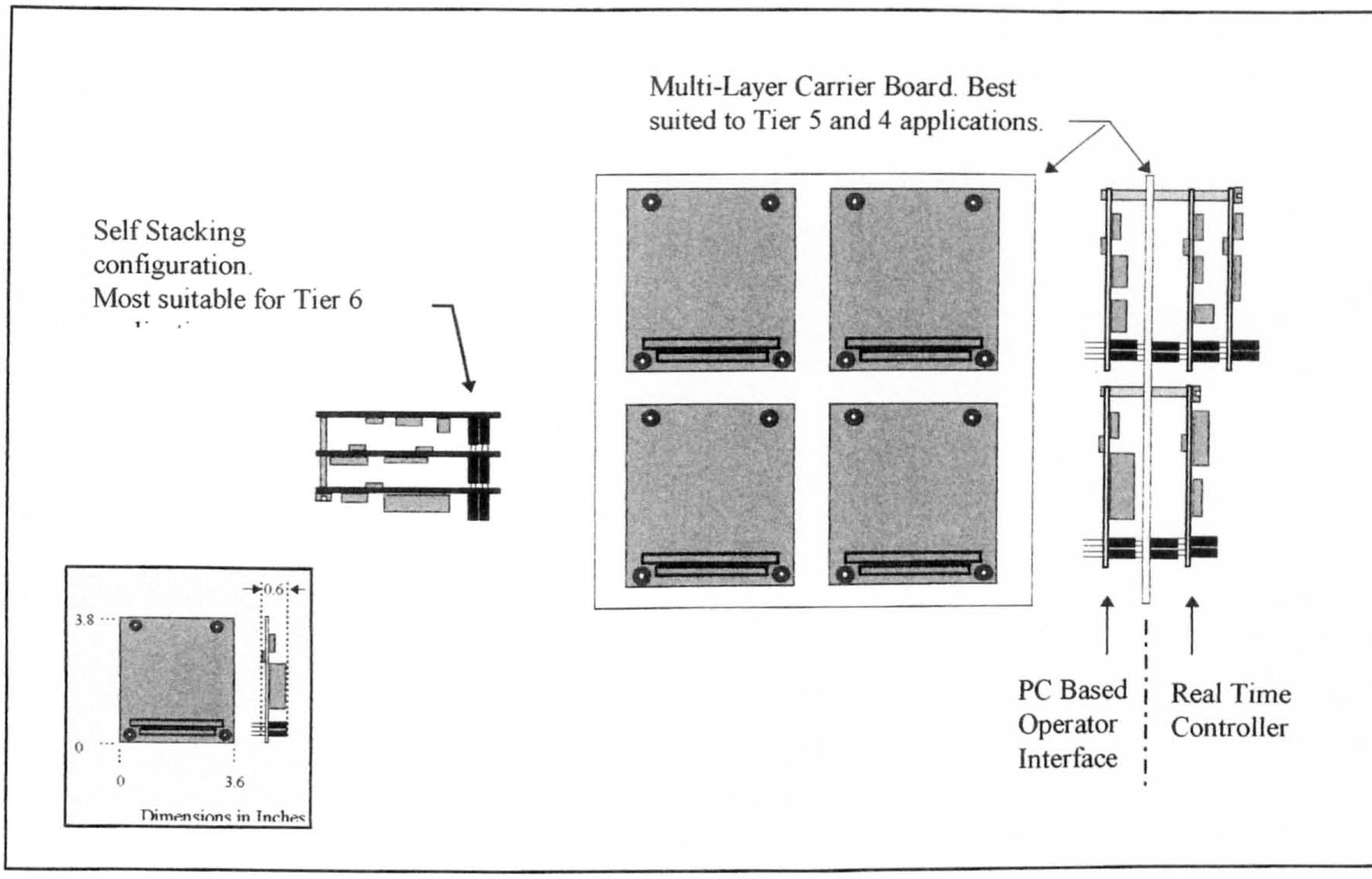
In the past the only practicable way to embed the PC architecture in space and power sensitive applications has been to design P.C. functionality directly into the product. This however runs counter to the NGCS specification's requirement for the use of *off the shelf* system components. A more robust and compact implementation of the PC bus is required without sacrificing full hardware and software compatibility with the PC bus standard. This allows the PC's hardware, software, development tools, and system design knowledge to be fully exploited.

A standard developed in response to this need is PC/104. It offers full architecture, hardware and software compatibility with the PC bus, but in compact (3.6" x 3.8") stackable modules. Although PC/104 modules have been manufactured since 1987, a formal specification was not published until 1992. Like the original PC bus, PC104 is thus the expression of a *de facto* standard, rather than the invention and design of a committee. In 1992, the IEEE started a project to standardise a reduced form factor of the IEEE P966 (draft) specification. The PC/104 specification has been adopted as the 'base document' for this new IEEE standard. The standard has recently been extended to offer PCI bus support whilst remaining 100% compatible with existing PC/104 modules.

In addition to the wide range of standard PC boards, for example CPU's, Ethernet, serial communications, solid state memory, a number of key suppliers familiar to those in the industrial control field produce PC104 boards. Boards are available for InterBus, Profibus and CAN (DeviceNet) and Indramat have a multi-axis motion control board using a SERCOS interface. Although adopting a standard open hardware platform (like the PC) offers many advantages, considerable application software engineering effort is still required to integrate control components into a functional system.

The prototype specification does not rigidly specify how the modules are physically configured, however, two typical configurations are illustrated in Figure 6-3. The configuration on the left is a self stacking configuration.. In this approach, the modules are used as compact bus boards, but without the need for backplanes or card cages. This configuration is best suited to Tier 6 applications. For larger machines possibly requiring two independent processors; (communicating through dual-port memory.) it may be the case that the PC/104 boards would be better plugged into a custom carrier board which can then be populated with application specific units. The multi-layer carrier board shown isolates the two PC's. In this way the left side of the carrier board could run Microsoft Windows® as the operating system, whilst the right hand side could operate independently using a deterministic real-time kernel.

Figure 6-3 Architectural Unit Carrier Board Configuration.



6.2.3 Standardized Interfaces

Clearly defined hardware and software interfaces are required if an open modular system is to be achieved. This design attribute is intended to allow specialist control suppliers to design and test products independently. Compliance with the specification will allow any sub-system to be added, removed or exchanged for another, without effecting other systems. Of course additional application software may need to be written particularly if the system is required to move tiers, for example, to accommodate the addition of a motion sub-system.

Where possible interfaces are avoided through the use of coupling analysis, for example, the specification dictates that ASCII text is sent to the operator interface unit so eliminating the need for a defined number to text interface found in contemporary systems. A second strategy is where possible avoid custom interfaces, for example focussing on interfacing via the sensor actuator or PC104 bus system.

An interface may be hardware, software or a combination of both. There are potentially three parts to each interface specification: hardware-system architecture (HSA), instruction-set architecture (ISA) and test and certification requirements. ISA determines the software requirements for a particular unit. The HSA deals with the hardware requirements. Finally the test and certification section will identify the functional tests carried out by an independent body and the certification procedure.

6.2.4 Maximized use of Bus Systems

Bus systems are used throughout the NGCS to eliminate the need for enclosure mounted input and output modules and to realise the widely recognised benefits of serial communication systems (e.g. reduced number of cables, improved diagnostics). Three bus systems are required to realise the *proof of concept* functionality. Table 6-2 highlights the bus systems used.

Table 6-2 Serial Bus Functions

Serial Bus Type	Function
InterBus Loop	Input and Output modules, Data tagging system, Operator Display, Connection to Specialist Gauging/Measuring units[24]
InterBus S (Fibre-optic)	Data transmission between controllers
SERCOS	Servo drive control and co-ordination.

[24] The protocol selected (InterBus loop) has the capability to process the data requirements of all devices listed in this category, however some devices are not commercially available at the time of writing. In practice InterBus S may have to be used for some devices.

6.2.5 Supporting Hardware Requirements

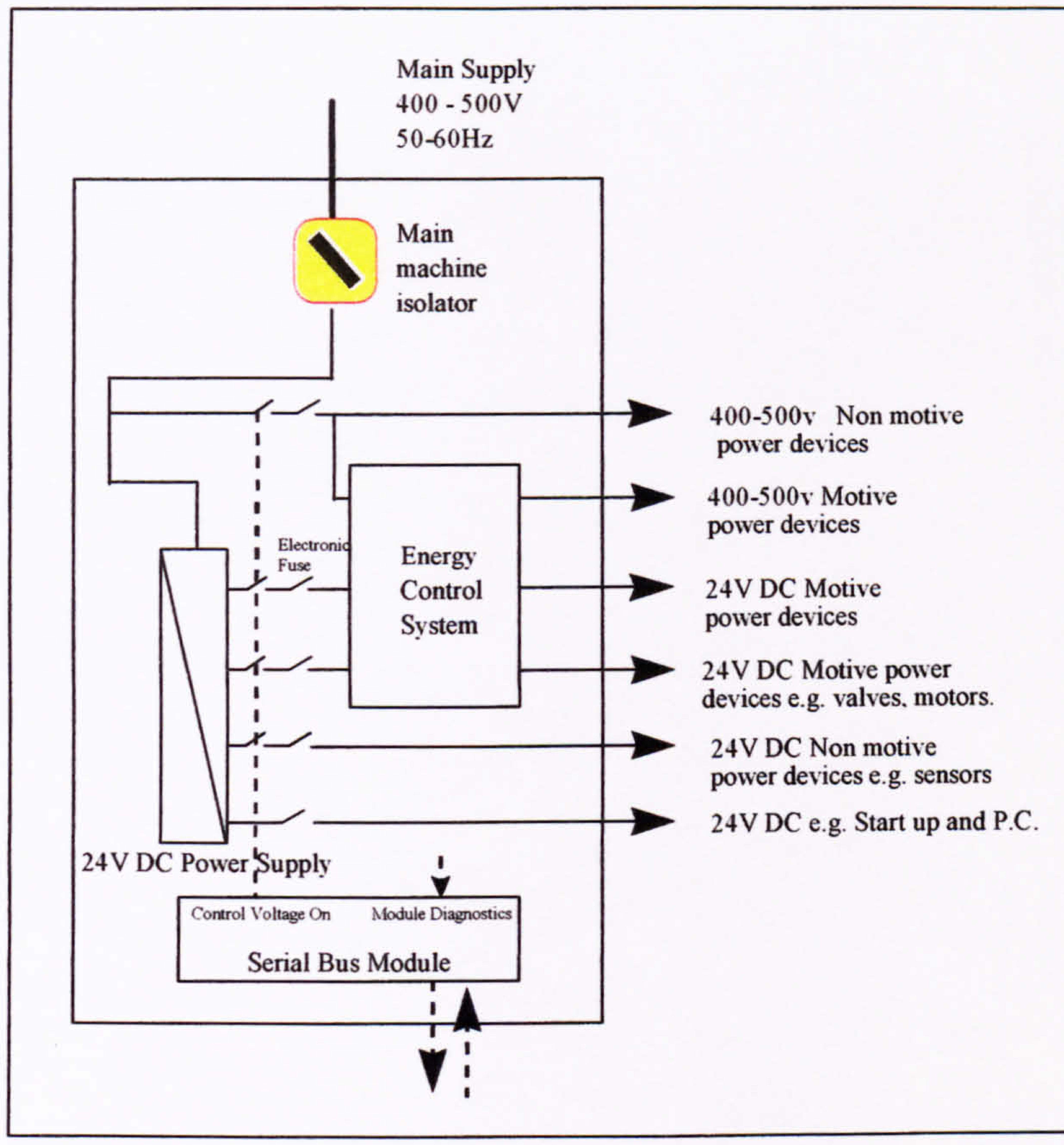
It is a common mistake to limit the design of a new control system to the main controller and associated units. The Sociotechnical analysis identifies several significant variables and relationships that produce requirements that must be achieved with supporting units which fall outside the scope of traditional PLC system modules. The units that must be considered in the design are: Machine Power Supply, Motor Controller Unit and Servo Axis Controller. The objective of the supporting hardware descriptions is to identify general requirements from which a detailed specification may be derived.

6.2.6 Machine Power Supply

The machine power supply unit is intended to fulfil the function of the main power distribution and protection devices normally associated with the main distribution cabinet. The unit must contain *quick change* connections and be environmentally sealed to allow mounting directly to the machine structure.

The input voltage and frequency tolerated by the unit must allow for global variation, a power supply within the unit transforms the supply to 24V DC. Modern machine tools require a number of segregated supplies in order to conform with safety, diagnostic and start-up requirements. The safety related supplies must be fed via a dual channel energy control system in order to conform to emergency stop and machine access legislation. All circuit protection should ideally be achieved by electronic protection to avoid the need for mechanical fuse links which may cause unnecessary production delays and be subject to errors if fuse links are replaced incorrectly. Control and communication with the unit is achieved via a serial bus loop integrated into the unit. The author anticipates the design of two or three different units of different power rating and a facility to allow units to be combined to make up the machine power requirement. Figure 6-4 shows the main elements of the unit and typical set of segregated circuits.

Figure 6-4 NGCS Power Supply



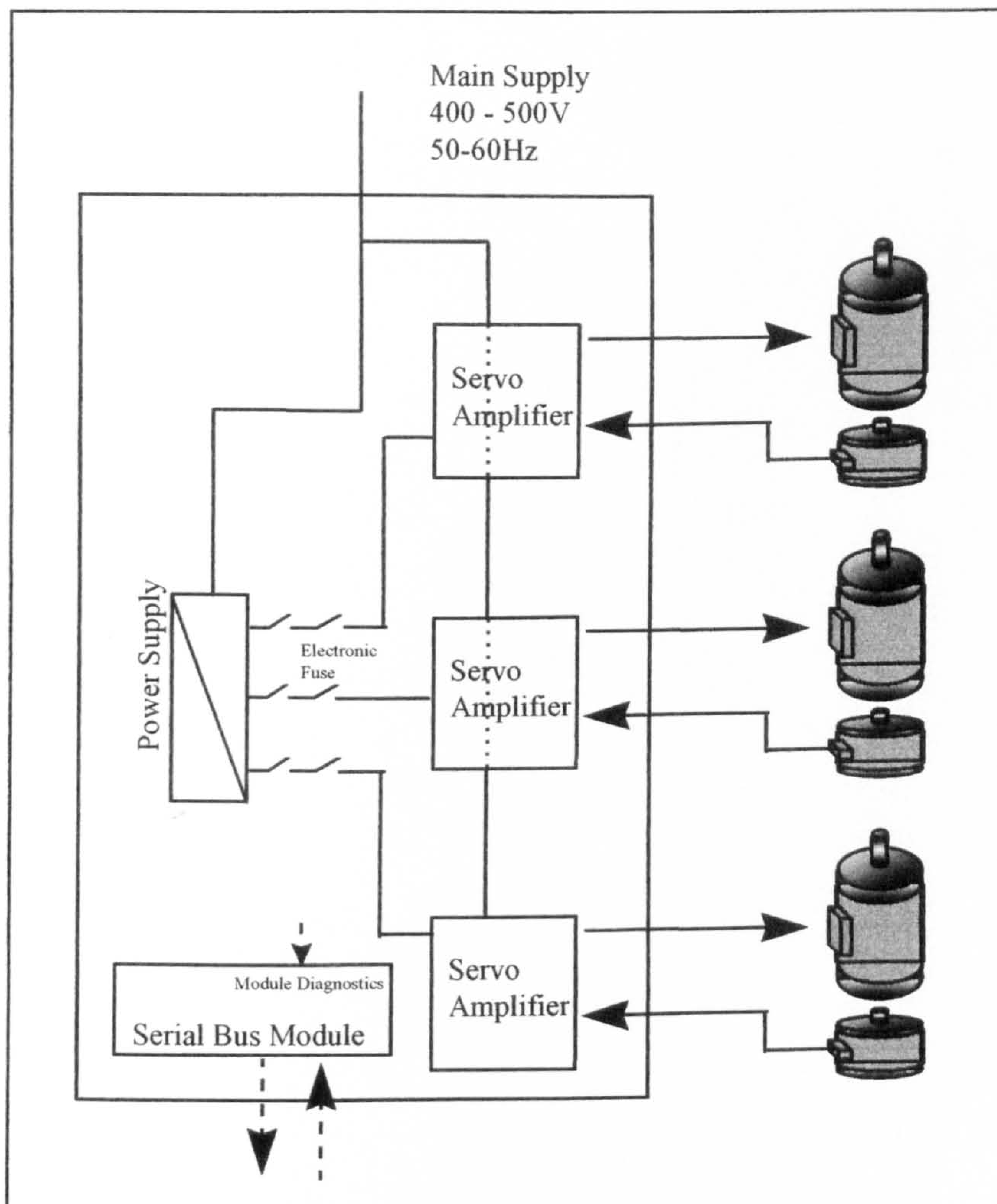
6.2.7 Motor Controller

The primary objective of the unit is to replace the motor starter and protection equipment found in a contemporary control enclosure. The modular unit is designed to be mounted directly on to the machine (adjacent to the motor). The general requirements with regard to: input voltage, quick release connections and environmental rating described in 6.2.6 apply to this unit. Machine mounting and multi-skilled operation and maintenance prohibits the use of discrete components for control and protection. The author proposes integrated communication and power control with circuit protection provided via the thermister found in modern motors.

6.2.8 Servo Axis Controller

In contemporary applications both enclosure mounted and machine mounted servo systems are available normally at the discretion of the specifying engineer. The NGCS demands machine mounted systems with general requirements regarding: input control voltage, quick release connections and environmental rating described in 6.2.6 apply to this unit.

Figure 6-5 NGCS Servo Control Unit



6.2.9 NGCS Application Software

The design attributes defined by the NGCS Framework have a significant influence on the application software and operator interface. A Tier 3 application must fulfil the real time requirements of CNC movements, discrete logic control, sensor actuator bus and provide a suitable user interface including operation, machine programming and diagnosis. In a contemporary control system this may require four unique programming environments. The methods used to programme and manage contemporary systems directly conflict with NGCS requirements. The NGCS application software is different to contemporary systems in two areas namely: the method required to load (and reload after module failure) software and the number and complexity of discrete software environments required to provide the appropriate functionality.

6.2.10 Automated Software Distribution

The management of application software for contemporary shopfloor control systems is often complex due to the fragmentation of functionality into a number of discrete programming and monitoring packages. Each package contains unique loading, archiving and diagnostic procedures. Both tasks involve the use of a P.C. and are not usually designed to be used by the machine operator.

Figure 6-6 demonstrates how the NGCS *manages* the complexity by storing all the application files onto a removable memory (PCMCIA) card accessible to the operator. Upon initialisation of the controller (power on) the System Initiation Unit (Main CPU) automatically distributes the application files to the appropriate intelligent units. The files that eventually reside on the main system CPU are compiled in their native form, whilst files generated for sub-systems (e.g. motion unit,) are produced in a standardised textual format (ASCII file). The time required to load and reload the program after a unit failure is dramatically reduced and designed to be achieved by the line operator. Diagnosis of unit failure (or machine failures affecting a unit) is designed to be fed-back via the Sequential Control unit giving the operator a single point of diagnosis, (Figure 6-7).

Figure 6-6 NGCS Application software Management

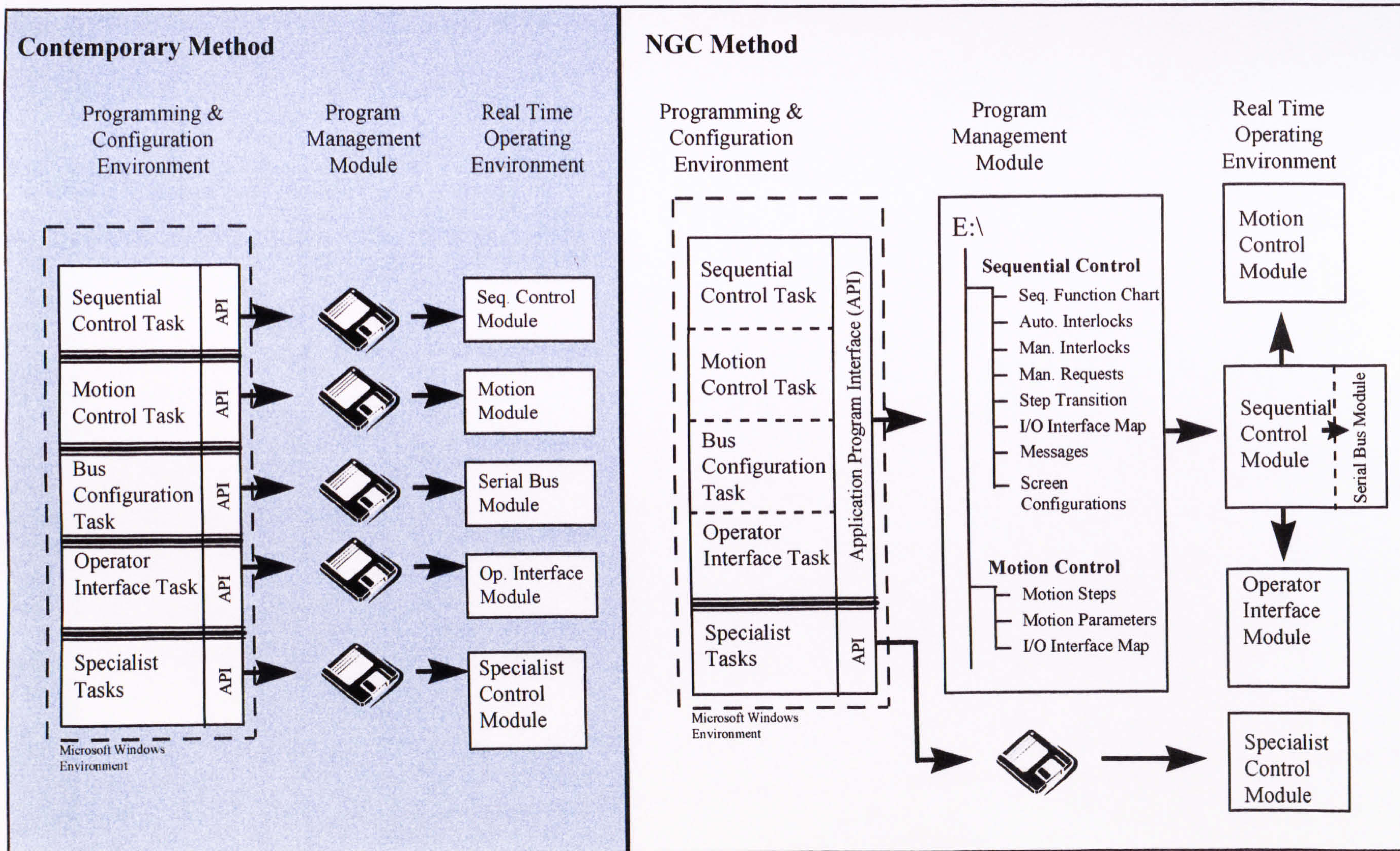
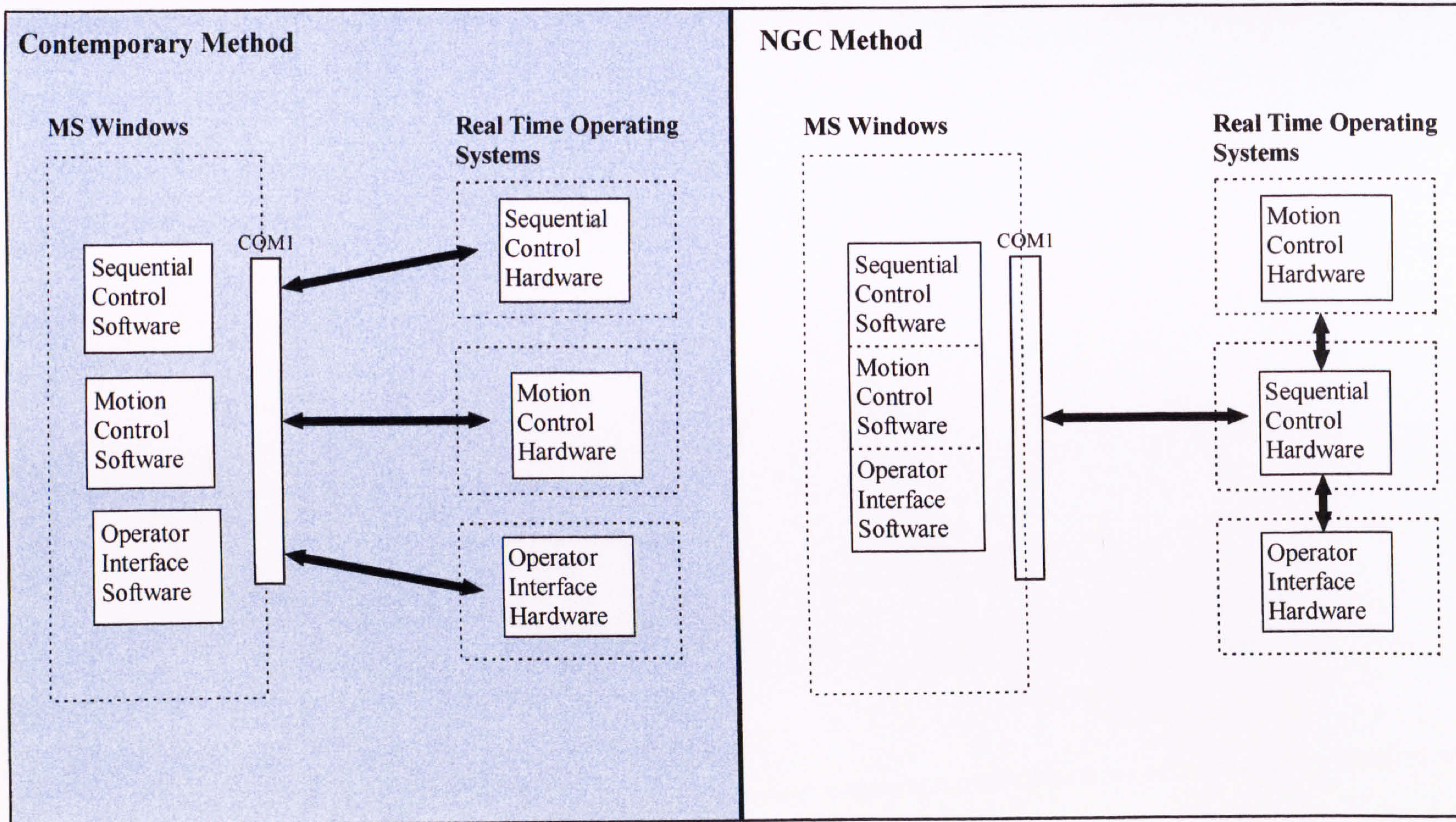


Figure 6-7 Data Management in Diagnostic/Monitoring Mode



6.2.11 Integrated Process Development Software.

Whilst hardware design has been moving along rapidly, reducing: price, size and increasing performance; industrial software techniques in comparison have been moving in small incremental steps. Brooks cites the following properties of software as major factors affecting its development: [Brooks 1987]

- Complexity: This is seen by many an essential property of software, in which no two parts are alike. The complexity is often arbitrary, being dependent upon the designer rather than the problem.
- Conformity: Software being pliable is expected to conform to the standards and limitations imposed by other components, such as hardware, or by existing software.
- Changeability: Software suffers from constant change throughout its life, partly because of the apparent ease.
- Invisibility: Because software is 'invisible,' any forms of representation that are used to describe it will lack any form of visual link that can provide an easily grasped relationship between the representation and the system. This not only constrains the ability to conceptualise the characteristics of software, it also hinders communication among those involved with its development.

In the past automotive manufacturers have tried to address some of the problems identified by Brooks through the imposition of structured application code. Complexity has been reduced in the programming and configuration environment due to the widespread use of Microsoft Windows™ as the operating environment. However, the NGCS design attributes require a single, embedded environment designed specifically for use by Manufacturing Process Engineers and Machine Operators. The integrated environment should support application configuration, programming, monitoring and problem diagnosis.

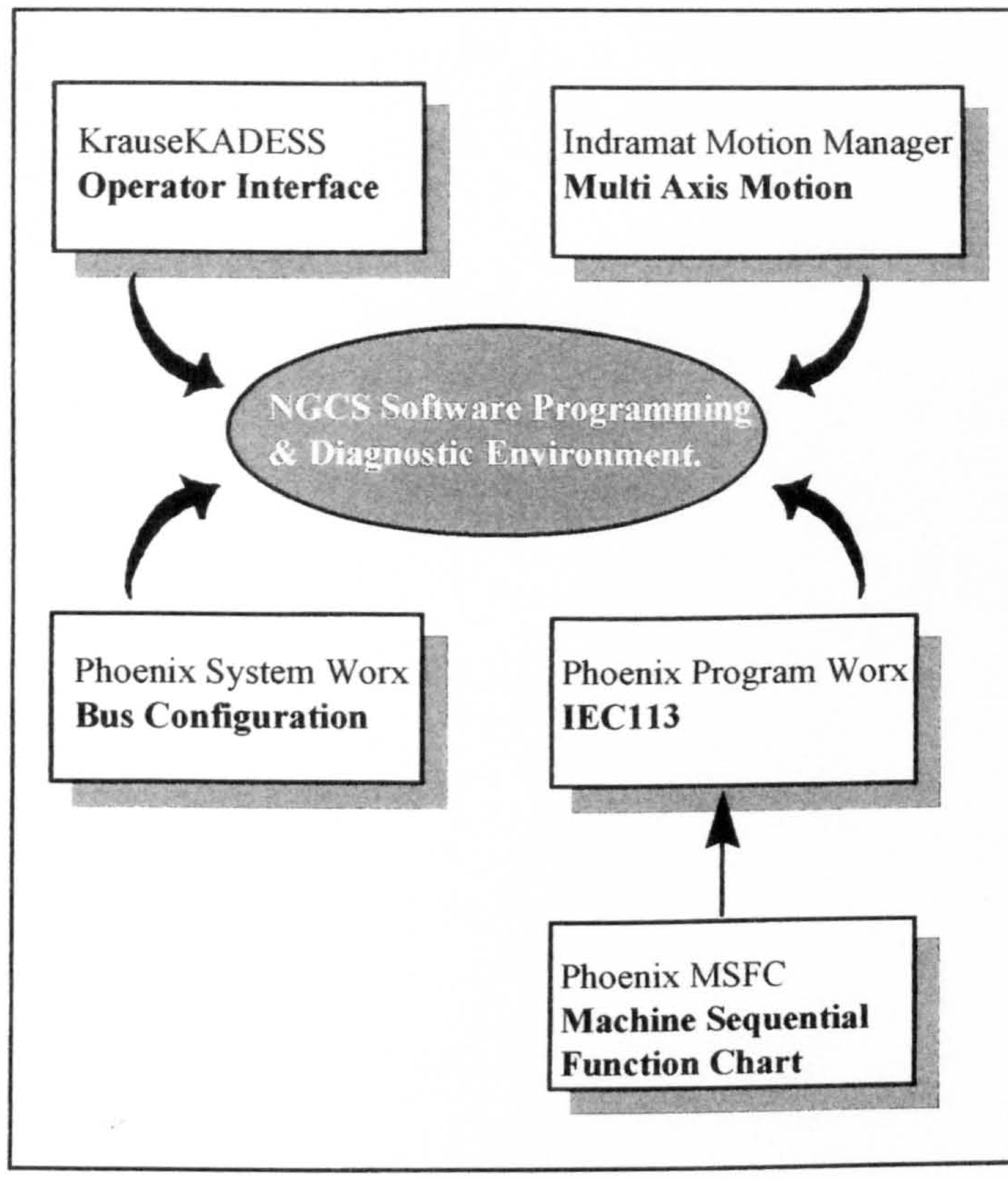
The author proposes the following design steps that go some way to achieving these objectives:

1. Categorise code into functional modules,
2. Arrange the modules into two classes, *application specific* and *system related,*
3. Where possible generate *application specific* code through the use of structured dialog boxes,
4. Move system related code to the background environment and standardise,
5. Identify the associated hardware unit where code will reside,
6. Integrate discrete (hydraulic, pneumatic or electrical) steps and servo motion steps into a single environment,
7. Apply software quality measures to the design for example coupling and cohesion analysis.

The model generated via the application of these design principles is significantly different to contemporary systems. Benefits of their application include: greater familiarity with the application software, reduced training, integrated diagnosis of problems, integrated environment for programming and configuration, highly regularised *application specific* code through the use of structured dialog boxes and finally a better *skills match* during the application and end user phases.

The design of a comprehensive programming environment is beyond the scope of this thesis, however by using the objectives to select suitable commercially available packages (Figure 6-8) many of the required attributes can be achieved (although not in an integrated form). The commercially available application software used on the prototype system is PCWORX® from Phoenix GmbH, Germany. The product is suitable for use with both Motorola® and Intel® based systems and utilises an IEC1131 base with an optional module known as Machine Sequence Function Chart (MFSC). Bus configuration is achieved with System WORX® again from Phoenix. The PCWORX and System WORX systems have a moderate level of integration. The operator interface environment selected is produced by J.A. Krause. The primary benefit of this tool over the many on the market is its relative simplicity and ability to accept ASCII text messages so allowing pre-configured display systems that do not require software download on initialisation. Finally the motion functionality is achieved with software Motion Manager from Indramat GmbH. This product allows the configuration of motion in a graphical form. The Author does not propose the following products as achieving the NGCS requirements however within the limited time and resource available the combination of modules together provide many of the features required of an NGCS Software Configuration, Programming and Diagnostic environment.

Figure 6-8 Selected Commercially Available Programming/Diagnostic Software



6.2.12 Proof of Concept System - Design Optimization Analysis

The *Feedback for Design Optimisation* process outlined in Chapter 4 recognises the existence of design flaws and seeks to adjust the design to eliminate or minimise their effect. Following each iteration of the design the *design optimisation* process is applied. In the case of the *proof of concept* system this is achieved by analysis, simulation and practical tests. On completion of the *proof of concept* system the following *active* elements exist and at this stage remain to be resolved.

Active element: Cost

Issue: Price comparison of tier 6 controller hardware compared to conventional PLC hardware is unfavourable. Whilst architectural benefits occur by maintaining the NGCS

Reference Architecture structure the author recognises the cost sensitivity of this section of the market.

Potential resolution/compromise: The most basic PC104 processor board available has been shown by the author to be more than adequate in terms of processing power. Suppliers tend to increase functionality of the boards rather than reduce cost. Future compromises may be to accept the cost penalty and by doing so maintain the NGCS principles, or integrate units together e.g. Central Logic Processing Unit and Sensor Actuator Bus in order to better optimise available processing time.

Active element: Quality

Issue: The selected sequential control software was unable to support integrated servo motion as part of its structure in the way prescribed by the NGCS specification.

Potential resolution/compromise: The prototype NGCS system used two separate programming packages which in their own way fulfilled many of the requirements laid down by the NGCS specification.

Active element: Quality

Issue: A number of supporting hardware units specified by the NGCS specification were not available at the time of the Prototype NGCS development. Theses included: machine mounted power supply, standard 3 phase induction motor control unit, and servo axis unit.

Potential resolution/compromise: The Prototype system was not connected to a machine therefore laboratory power supplies could be used. A machine mounted industrial power supply is required prior to implementation on a machine tool. The control of induction motors was achieved by mounting bus connected input and output blocks adjacent to standard industrial contactors. A small control enclosures would be required to house the components on a machine tool incurring a cost penalty. The author proposes the development of a purpose designed unit that contains: communication, control and motor protection elements.

Active element: Quality

Issue: The Process Development Environment used to program the sequential part of the control problem stopped short of NGCS specification requirements. The structure defined initial *type* (of the step) and messages however several lines of IEC1131/3 code was required to identify the assigned input and output variables and to drive standard variables used in the background function blocks.

Active element: Time

Issue: During system set-up the time required to assign input and output points to internal variables did not compare favourably to a proprietary system that has predefined input/output structure and definition..

Potential resolution/compromise: The open structure of the serial bus system used dictates the need for user defined parameters. No improvements were made.

6.3 Application of the NGCS Framework to an Engine Assembly Line

This section describes Simultaneous Engineering led by the author with the aim of realising the NGCS Framework principles on a new high volume assembly line at Ford Motor Company's Dagenham Engine Plant. The section begins with a brief resume of the facility and the conditions that led to the NGCS framework being selected. The Simultaneous Engineering method and structure is outlined and each major application tier discussed. The Proof of Concept system is re-examined in light of the practical application and new design features are identified and discussed. In the final section of the chapter the design of the new control system is evaluated and the results critiqued against a similar contemporary assembly line control system.

6.3.1 Background

The intended target application area was a high volume Engine Assembly Line at the Ford Motor Company Limited. The control applications found on the assembly line range from simple engine transport systems to complex multi-axis systems with a number of complex sub-modules. An engine assembly line is a large and complex manufacturing system, therefore a full presentation of each system component is beyond the scope of this thesis. NGCS elements that highlight pertinent issues addressed within the thesis are discussed in some detail. Whilst several S.E. teams are discussed it should be noted that only the Controls Team followed the NGCS Design Framework Principles.

The Puma Engine manufacturing facility (see Figure 6-9) is designed to produce a new range of four cylinder diesel engines at a volume of 450,000 units per year. The assembly line is split into three main areas: Cylinder Head assembly, Engine assembly, and Engine test. The line consists of: complex machines (tier 4), elementary machines (tier 5) and approximately 200 metres of engine transport conveyor (tier 6). The line is segmented into 8 zones to facilitate monitoring and control, requiring a zone controller (tier 3) for each.

Figure 6-9 Puma Assembly Line

Several events combined to provide the opportunity for a major change from Ford Motor Company's existing Assembly Line control system strategy, namely:

1. Ford had been using the same control system on Engine Assembly lines for eight years and the same control supplier (Siemens) for twelve years. The control system had progressed through two generations and numerous upgrades, however the supplier had informed Ford that the current system would in the near future be replaced. Production of the control system was planned to cease by the year 2001. Whilst supplies were guaranteed for the life of the engine program, Ford were particularly concerned with regard to mid life upgrade of the engine facility.
2. The engine program was to be one of Ford's first programs to fully implement its 'Ford Production System' principles. This strategy required the use of multi-skilled production teams for which the existing control system was not suited. The existing system was recognised by Ford staff as one of the most powerful and flexible systems available, however it also had a reputation for being one of the more complex, [Chipperfield 1998].
3. The third major factor was the imposition of an aggressive affordable business target which generated the need for a significant investment saving over the previous program. The impending obsolescence of the existing product gave little opportunity to achieve this goal.

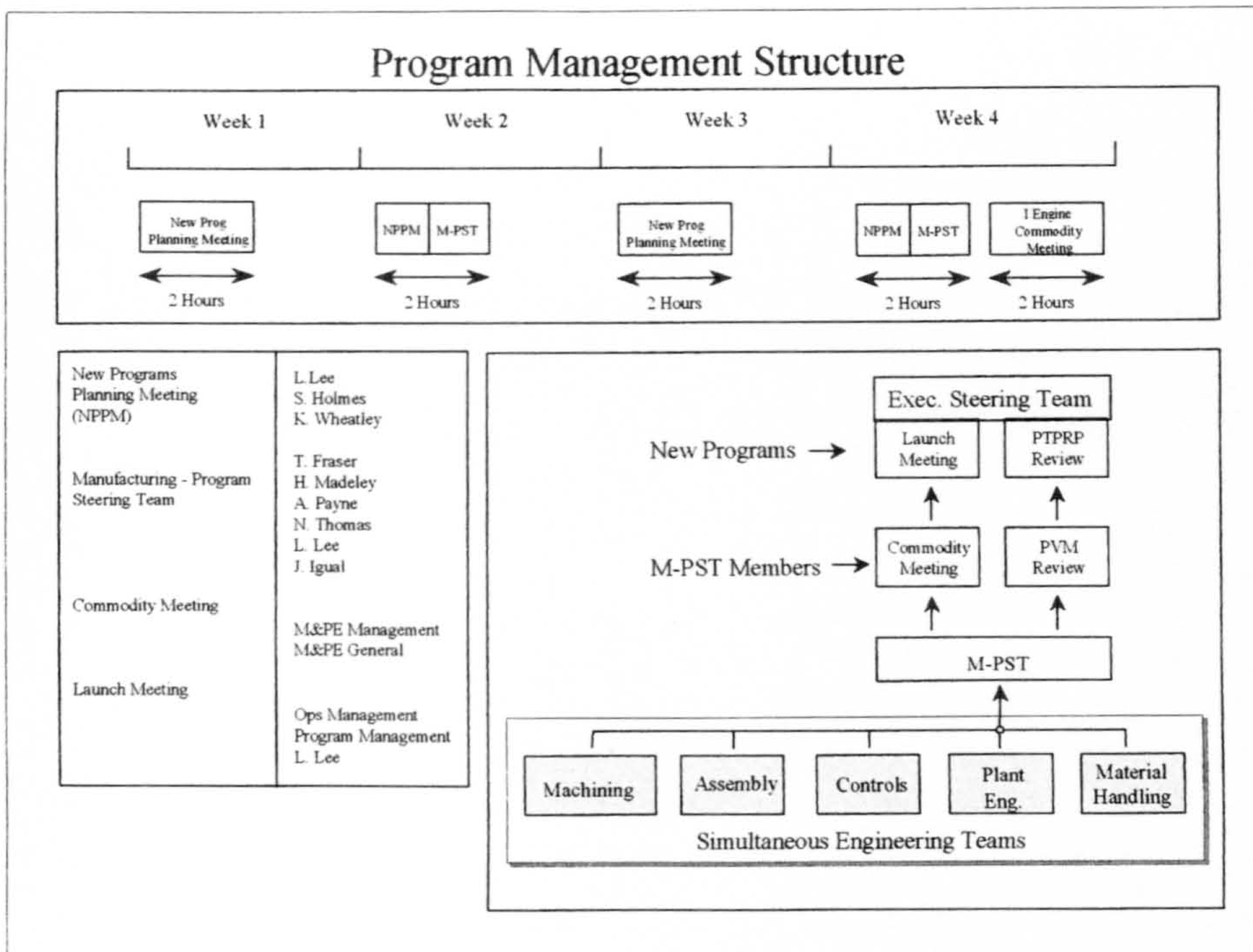
These issues led to Ford's Manufacturing Engineering activity to be tasked with investigating alternative systems. The NGCS Design Framework was presented by the author to Manufacturing Management at Ford and the approach was selected as one of five potential solutions. Following detailed comparison it was selected as the primary route and the author asked to lead the Manufacturing Controls Simultaneous Engineering team.

6.3.2 Simultaneous Engineering (S.E.) Method and Structure

The Simultaneous Engineering (S.E.) method used by Ford is a team based approach, with the active involvement of machine tool builders (known as *first tier* suppliers), technology providers (known as *second tier* suppliers) and Ford Engineering Staff. The *first tier* supplier for the Puma Assembly line was J.A. Krause GmbH an Assembly System Manufacturer from Bremen in Germany. The Ford Engineering Staff were drawn from a Central Staff organisation and Engineering staff from the Manufacturing Plant, (In this case Dagenham Engine Plant.). The team was tasked with taking responsibility for the delivery of the Assembly Line from initial planning and approval, through engineering and installation, and finally onto launch of the facility in the plant.

The Program Management team was based on the structure specified in the NGCS Design Framework, namely: The Simultaneous Engineering Team reported to a Manufacturing Program Steering Team (M-PST) who in turn interfaced to the Executive Steering Team (EST). The structure used is shown in Figure 6-10.

Figure 6-10 Simultaneous Engineering Team Structure



Due to the time constraints placed on the team the *second tier* control system technology partners were not selected until the Technical Requirements Analysis was in progress. The selection criteria shown in Figure 6-11 were based on NGCS architectural and technological features. At this stage the SE Team also had a clear view of the required control system attributes. The amount of change from Ford's traditional approach can be judged by the fact that only one technology partner from the previous program was thought to have the necessary products to fulfil the NGCS design requirements.

Having assembled the full S.E. team, detailed implementation workplans were developed for each element of the control system. Following the engineering and test phases of the process a test loop was built that utilised all elements of the system. The primary functional elements forming each tier are shown in Figure 6-12.

Figure 6-11 Second Tier Supplier Selection

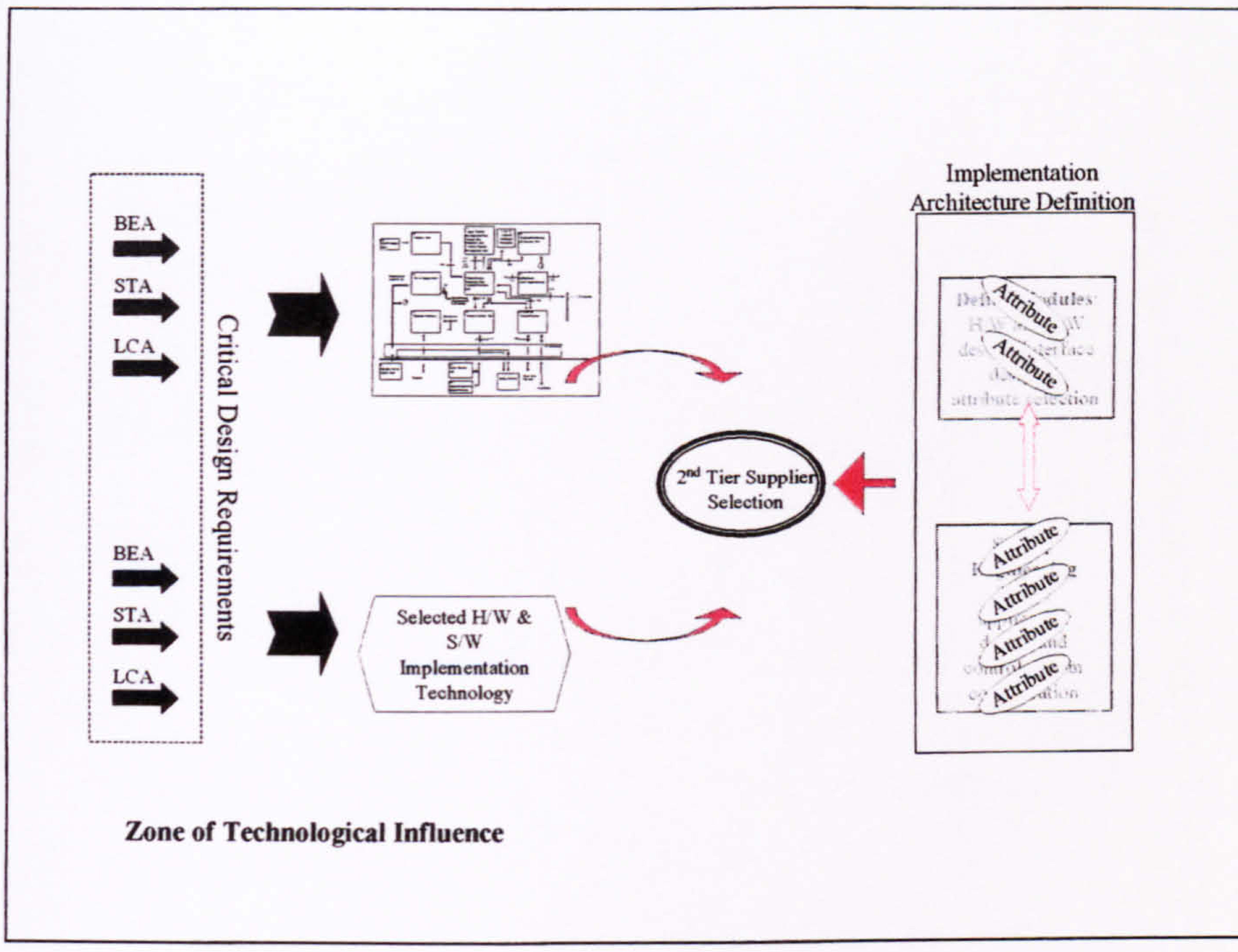


Figure 6-13 shows a small section of conveyor system and three elementary assembly machines (two rear facing, one front facing). Many of the hardware changes from a contemporary system implementation are immediately evident the primary visual impact being the elimination of the machine control cabinets. The extensive use of serial network technology, field mounted input and output system and IP54[25] sealed units allows the machine mounted control elements to be distributed around the machine. Quick change connector systems allow units to be maintained by the machine operators and application software that automatically downloads when power is applied to the system completes the attributes applied for multi-skilled maintenance of the system. Due to the time constraint on the program interfaces and devices compliant with the NGCS specification could not be implemented to some of the more complex devices. For example a suitable bolt rundown unit could not be developed in time.

[25] IP54 - Equipment sealing standard to prevent the ingress of water or dust.

Figure 6-12 Functional Elements

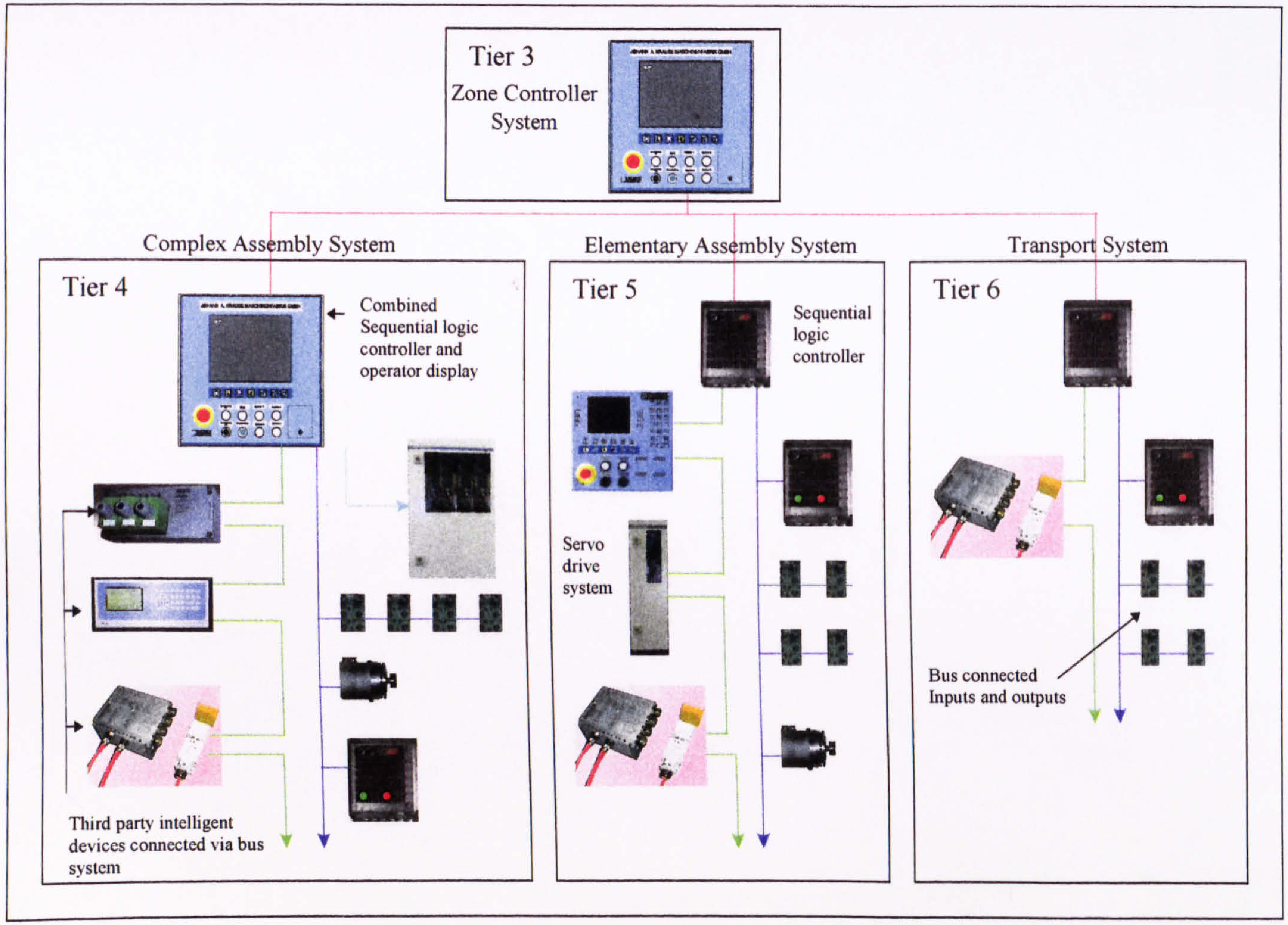
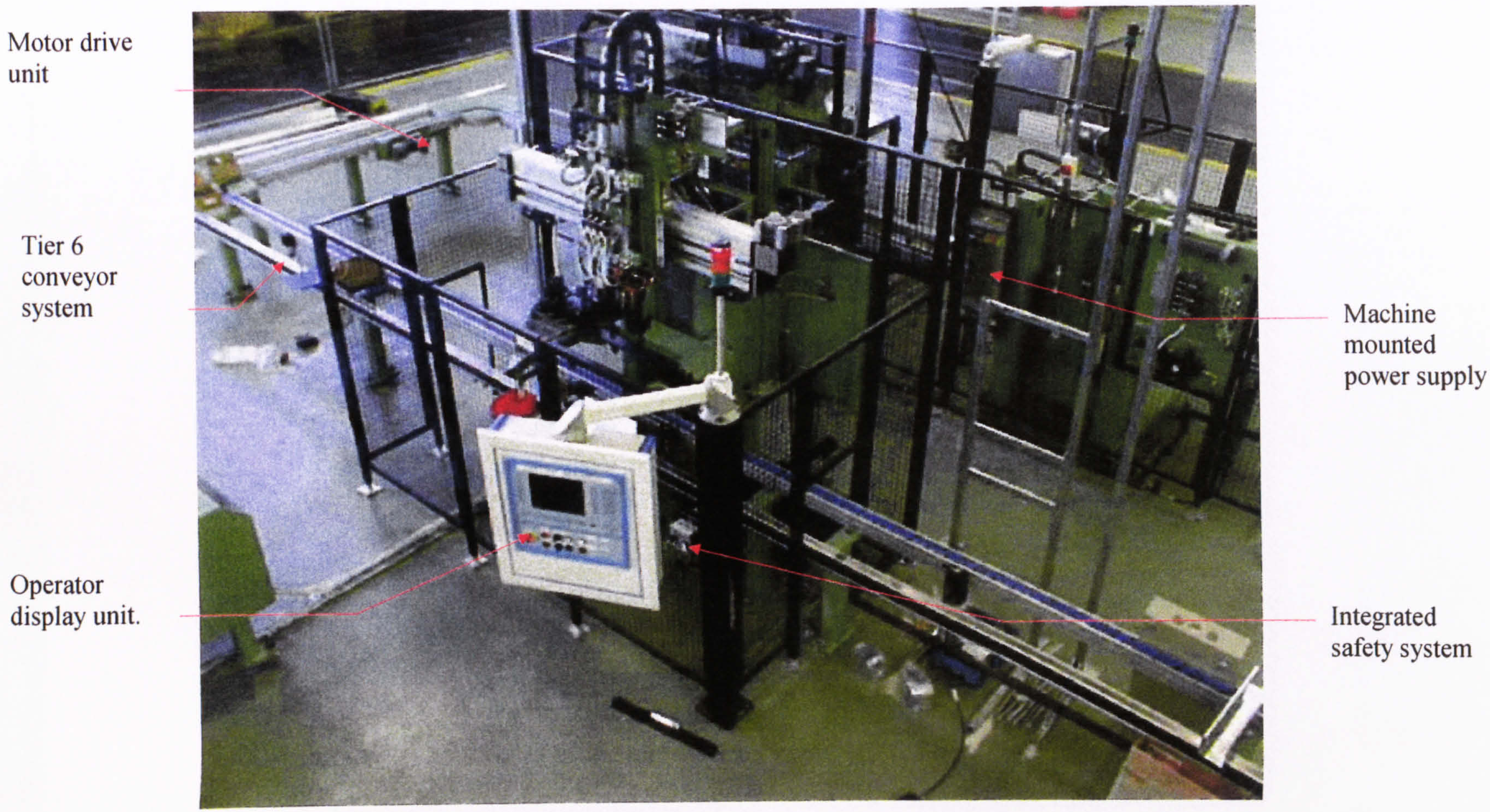


Figure 6-13 Puma Assembly Stations



6.3.3 Engine Assembly System - Design Optimization Analysis

This section considers each of the *active elements* identified during the development of the NGCS Proof of Concept System and outlines the resolution or compromise implemented by the S.E. team.

Active element: Cost

Issue: Price comparison of tier 6 controller hardware compared to conventional PLC hardware is unfavourable.

Resolution/compromise: The sensor actuator bus unit uses a Motorola processor. Engineers from Phoenix Contact were able to use available processing time on the bus controller to run the sequential control software. The selected software was able to run on both Motorola and Intel based systems so allowing a common programming software structure from tier 6 to tier 3. This action reduced the cost of the tier 6 and 5 controller whilst maintaining software commonality.

Active element: Quality

Issue: The selected sequential control software was unable to support integrated servo motion as part of its structure in the way prescribed by the NGCS specification.

Resolution/compromise: The prototype NGCS system used two separate programming packages which individually fulfilled many of the requirements laid down by the NGCS specification. Given the time constraints imposed on the S.E. team a single integrated sequential and motion software package was not achievable.

Active element: Quality

Issue: A number of supporting hardware units specified by the NGCS specification were not available at the time of the Prototype NGCS development, including: machine mounted power supply, standard 3 phase induction motor control unit, and servo axis unit.

Resolution/compromise: The machine mounted industrial power supply and motor control unit were specified and developed by the team. Currently available servo technology was packaged into a sealed enclosure suitable for mounting on the machine structure. Whilst this action allowed distribution and machine mounting, compromises existed in the final design with regard to multi-skilled maintenance.

Active element: Quality

Issue: The Process Development Environment used to program the sequential part of the control problem stopped short of NGCS specification requirements. The structure defined initial *type* (of the step) and messages however several lines of IEC1131/3 code was required to identify the assigned input and output variables and to drive standard variables used in the background function blocks.

Resolution/compromise: Within the resource and time constraints of the project the team optimised the software to encompass many NGCS requirements.

Active element: Time

Issue: During system set-up the time required to assign input and output points to internal variables did not compare favourably to a proprietary system that has predefined input/output structure and definition..

Potential resolution/compromise: The open structure of the serial bus system used dictates the need for user defined parameters. No improvements made since this additional configuration step is inherent in providing a controller which is configurable for any *open* serial bus system..

In addition to the 'active filters' identified, other compromises were required namely:

Active element: Quality / Cost / Time

Issue: The complexity of the serial network systems was increased due to the poor integration of some elements into the sensor actuator system. The preferred serial bus system selected by the team was the two wire Interbus Loop™. The system contained the quick connection and multi-skilled properties required by NGCS however at the time of application the product had only been on the market for a short time, hence not all the required system interface devices were commercially available for integration.

Potential resolution/compromise: The compromise required the introduction of a second field actuator bus utilising a five wire technology. The additional complexity potentially impacts on quality, in addition a cost filter is imposed due to the additional bus driver and pre-made cables required when using the five wire technology. The older five wire system did not contain the same diagnostic features and hence time penalties may be incurred during a machine failure.

Active element: Quality / Cost / Time

Issue: Quality testing and certification carried out by Ford restricted the types of 'nutrunner' technology that could be considered for use. This restriction led to the selection of bolt rundown technology that did not meet NGCS Framework requirements. The selected equipment could not accept a network connection and was not designed to be maintained and adjusted by multi-skilled staff.

Potential resolution/compromise: The compromise required the introduction of field mounted input and output blocks to communicate with the unit. Additional complexity was managed by transferring data via an RS232 link and presenting information to the operator on the machine operator display unit.

6.4 Summary

This chapter discusses the application of the NGCS Design Framework to a *Proof of Concept System.* Control system attributes that differ from conventional manufacturing control systems are identified along with elements that require optimization prior to the system being applied to a *real world* application. The second part of the chapter describes the application of the NGCS Design Framework to an Engine Assembly Line. Issues identified during the development of the *Proof of Concept System* are discussed and where possible resolved in the Engine Assembly Line application.

The practical application of the Design Framework identifies six tiers of architectural definition. Four application tiers are identified ranging from a high level zone controller at tier 3 to a simple transport system at tier 6. During the application stage opportunities and improvements surface that deviate from the defined architectural principles. These changes may have high practical value in terms of performance or initial cost, however hidden *life cycle* costs are likely which may be undesirable to the system's user. Where possible the initial *proof of concept* controller presented adheres closely to the NGCS Framework principles. Practical considerations and compromises necessary for factory-installed systems are considered during the application of the process to the Engine Assembly Line.

Finally a design optimisation process is used to identify cost, quality and time elements that may need to be applied by end users to optimise the system for real world application. The *active filters* identified as a result of the NGCS Proof of Concept system are addressed and where possible resolved or compromises sought. A number of issues arose during the application phase that require future work These issues are discussed in Chapter 8.

The next chapter discusses the technical and operational performance of the applied NGCS control system by comparing it with a conventional control system application.

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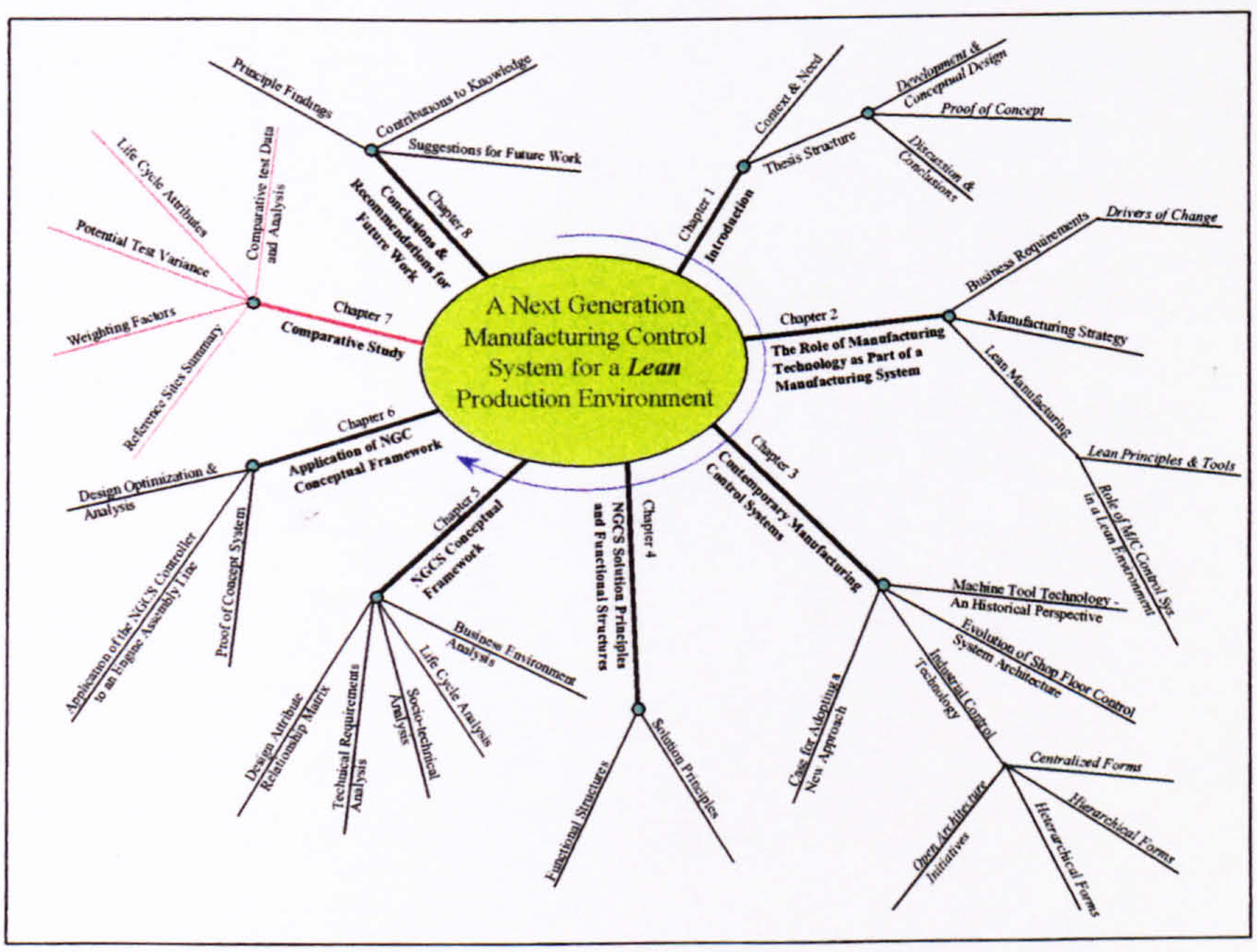
CHAPTER 7

NGCS COMPARATIVE STUDY



7. NGCS Comparative Study

7.1 Introduction

The previous chapter described the application of the NGCS Design Framework to a *proof of concept system* and high volume engine assembly line. The aim of this chapter is to critically discuss: the technical and operational performance of the Next Generation Control System by comparing it with a conventional shopfloor control system.

To fulfil this aim a series of quantitative measures of technical and operational performance are specified. Two reference sites are used to carry out the tests. Factors influencing the life cycle effectiveness of the systems are consolidated into seven evaluation criteria, namely: system flexibility, system agility, operational efficiency, scalability, availability, performance and cost. A *weighting factor* is introduced to distinguish the importance of each criteria to the overall system performance. The test and measurement method is given and where possible a quantitative scaling system used to present the results. Further detail related to the test criteria and results are presented in Appendix C.

7.2 Reference Site Summary

Two Ford Motor Company sites were used to compare the NGCS and conventional control system solutions. Both sites use the same Ford Motor Company *lean* manufacturing model. Site one produces a four cylinder in –line gasoline engine. The engine produced by site two is a diesel engine, however it has a similar architectural configuration (in-line four cylinder) with a slightly higher product complexity and lower volume. Despite these slight differences the two sights have comparable levels of control system complexity and the number of machines at each tier of architectural definition is similar. A summary of the sites is shown in Table 7-1.

Table 7-1 Test Sites Summary

	Site 1 (Research date: 5/98)	**Site 2 (Research date 10/98)**
Location	Ford Motor Company Limited, Bridgend.	Ford Motor Company Limited, Dagenham.
Line	Zetec S.E.	Puma Engine.
Product Complexity	Inline 4 cylinder, 16 valve gasoline.	Inline 4 cylinder, diesel.
Equipment Job 1 date.	5/98.	5/99.
Production volume	550,000 engines per year.	450,000 engines per year.
Operating philosophy	*lean production* methods. Team based multiskilled operators.	*lean production* methods. Team based multiskilled operators.
Manufacturing Control System	Contemporary. Siemens PLC and pre-programmed units on conveyor system.	NGCS Framework.
Equipment Manufacturer	J.A. Krause Bremen.	J.A. Krause Bremen.

7.3 Evaluation Criteria

The comparative testing criteria is divided into seven attribute measures, namely: System Flexibility, System Agility, Operational Effectiveness, Scalability, Availability, Real Time Performance and Purchase Cost. The definition of each measure is given in Table 7-2. The comparative *task detail* is set for each of the seven measures and an appropriate weighting factor applied. The weighting factors are designed to recognise that each attribute has a different level of influence on the life cycle cost of the system. The weighting value is derived from an assessment made by a cross-functional team with representatives from machine tool builders, system integrators and end users[26]. Comments and test results for each of the seven measures are shown in Table 7-4.

7.4 Potential Test Variance

Few studies are able to examine intensively and in depth all instances of a given research problem, [Marshall 1994]. The author recognises that the data produced as a result of the comparative tests may be influenced by a number of practical constraints, namely:

1. Insufficient sample size - The tests were carried out largely in a running manufacturing plant therefore the operator and application sample size was restricted to two operators from each site and a comparison of one machine type. A measure of independence was established through the use of an independent test supervisor that monitored all tests at both sites for consistency.
2. Variance in operator experience - The multi-skilled operators at site 1 were more experienced than those at site 2. Although the formal training given to both sets of operators was comparable the operators from site 1 had spent additional time working on the production facility. At the time of the test the site 2 production facility was in a launch phase and hence production experience was limited.
3. Inconsistency in test methods - Where the task could not be completed by the operators this is noted within the test results. The manufacturer of the equipment was asked for a *method statement* and a judgement made by the Ford training staff with regard to feasibility and time required. The two training staff activities may have judged the required time to be different. Note: Software training was carried out by the same instructor for both systems and sites therefore a measure of consistency is maintained for this criterion. Practical reliability data was available for the contemporary equipment via the Ford Production Monitoring and Failure systems. The NGCS equipment had not been used in production at the time of the tests; therefore MTBF values for site 2 were derived from manufacturer data sheets.

[26] Note: The cross functional team used to set the weighting values consisted of the Puma Simultaneous Engineering team and in addition three metal cutting machine supplier. End users included both Plant and Central Staff activities from the Ford Motor Company Limited.

Table 7-2 Evaluation Criteria

Attribute/Measure	Task Details	Weighting
System Flexibility The *System Flexibility* evaluation criteria assumes that the manufacturing control system was originally selected to encompass all known and planned machine functionality. Therefore the measure of a systems flexibility is taken to be its ability to be modified and reconfigured using equipment from the original manufacturer. The ability of a manufacturing control system to rapidly adapt to known product variance / complexity. (i.e. 2.0L and 1.8L models).	The sum of the time in minutes to : Add step to sequence, delete step from sequence, configure system for 40 additional input / output points, increase processor speed (scan rate) by 20%, add one motion axis, increase memory capacity by 20%.	15
System Agility Assumed that the manufacturing control system may not have been selected to encompass all functionality. Therefore The measure of a systems flexibility is taken as its ability to be reconfigured with third party products. An agile facility is by nature flexible but can in addition can rapidly adapt to unforeseen change. (i.e. the introduction of a new material or product feature).	The sum of the time in minutes to : Configure system for 40 additional 3rd party input / output points, add 3rd party motion functionality, change real time software manufacturer and write one simple motion step.	15
Operational Efficiency Time required to train a multi-skilled operator to carry out specified maintenance actions and restart the machine cycle A measure of the ability of an advanced manufacturing technology to integrate with the operating environment found in a *lean* manufacturing facility. E.g. Team based multi-skilled operating environment requiring : Minimal Training (low operator complexity, support continuous improvement,) Effective diagnostics,	*Training* :. Change processor, change power supply, change I/O point, change serial bus card, update an operator message, update a motion feed position. Assessment of training requirements for operator based and skilled maintenance staff. The testing included a judgmental decision with regard to course difficulty using training staff experience. *Diagnostics* :Ability of the system to provide system (hardware) faults and process (actuators, switches etc.) faults. System Faults: Serial bus failure, memory error / loss, processor failure. Process faults: Short circuit protection 9input and output), Switch failure, pairs check (both switches made). Final rating to be average of the three specified criteria.	15
Scalability The ability of a system to match functionality / process complexity with control system functionality	Map of ten functional increments representing increasing process complexity against available control configuration.	10

Table 7-3 Evaluation Criteria (Cont)

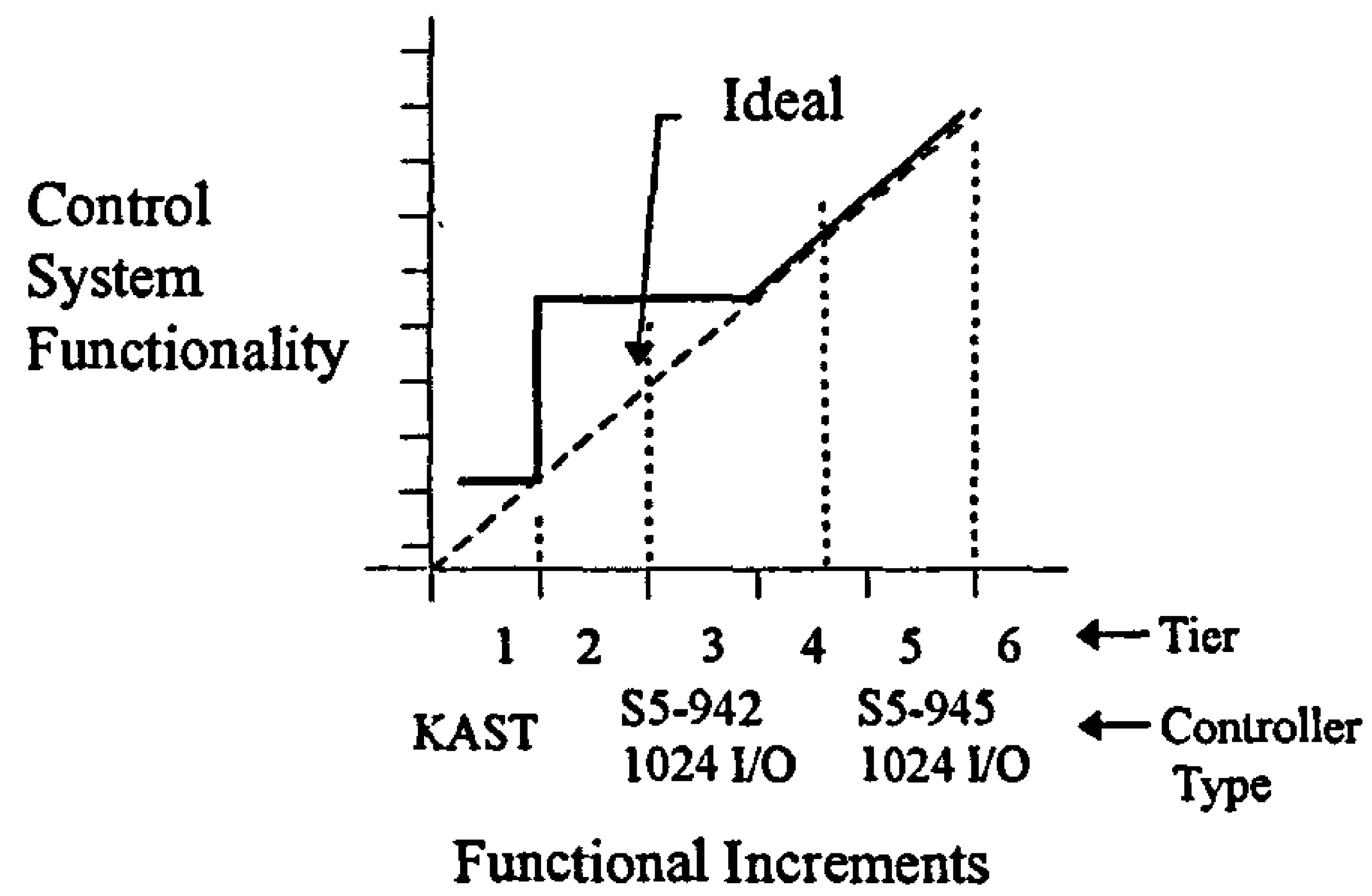
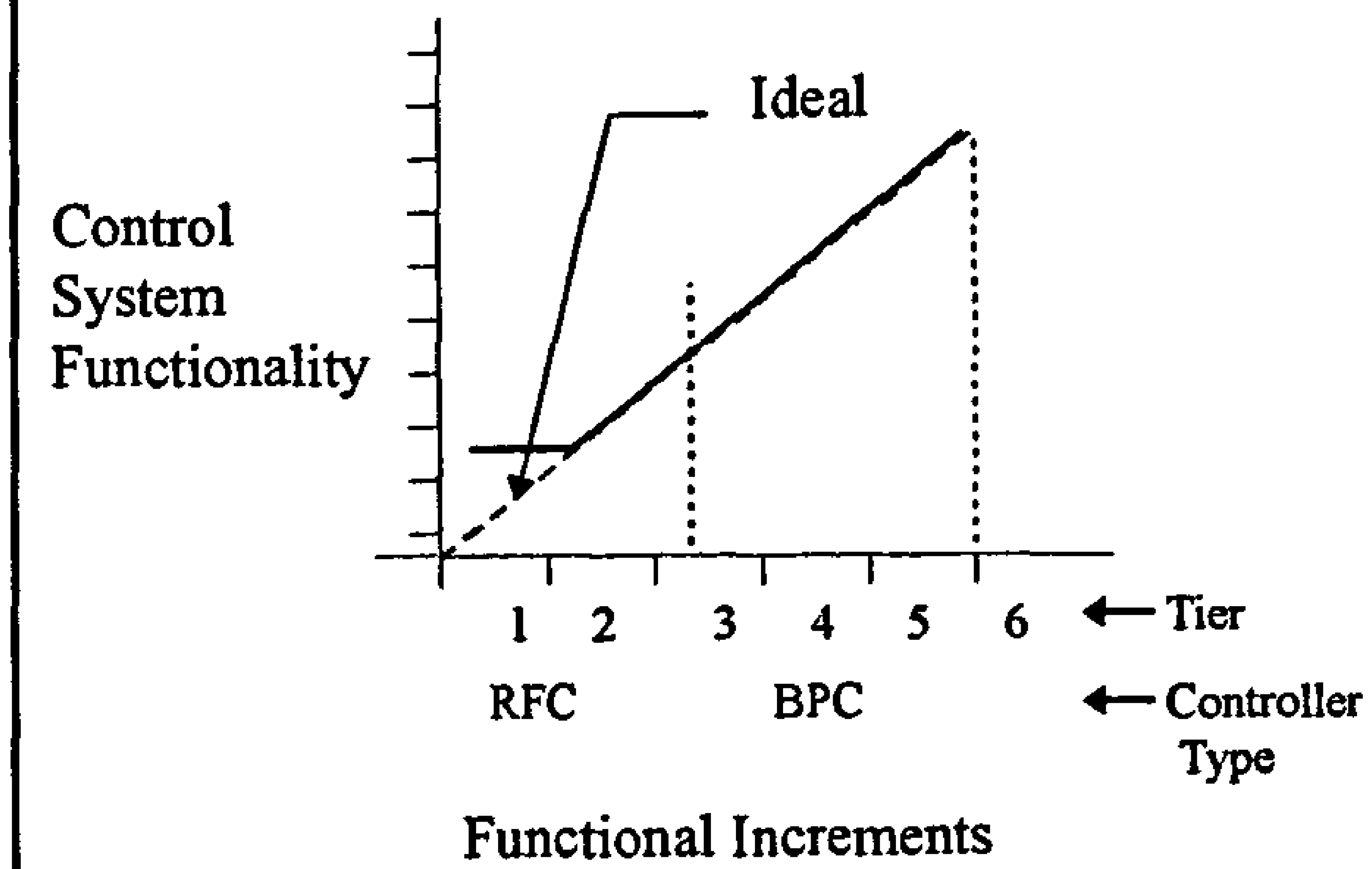
Attribute / Measure	Task Details	Weighting
Availability A measure of the degree to which a system is in an operable state at any point in time. Specifically , the percentage of time that the machinery will be operable when needed	This comparative test was based upon an Assembly line model utilising the Witness Simulation Software. The existing model was run using mean time between failure (MTBF)and mean time to repair (MTTR) data collected from an existing Assembly line [Zetec S.E. Valencia Engine Plant, Ford Motor Company]. It was assumed that the reliability (MTBF) of the Contemporary and NGCS systems were comparable. The MTTR was varied based upon tests carried out to measure the time required to exchange the NGCS. Results are based upon the assumption of multi-skilled operation. The model run time was 42 shifts.	20
Realtime Performance Measure of cyclical scan rate of the machine controllers under test	Scantime comparison between Site1 (SiemensPLC based system) and an equivalent 486 PC based controller. Scan test carried out on same site 1 machine using 486 PC based controller (similar hardware to that used on site 2). All external hardware remained constant (i.e. linked to controller via serial sensor actuator bus). Real time controller Phoenix PC Worx™. Sequence of operation identical. Original program structure emulated wherever possible. Result represents average scan value over ten machine cycles.	10
Purchase Cost The purchase cost of a control system	Sum of the list prices of three specified configurations (Conveyor, Small Machine, Large Machine) multiplied by the number of each type used in a specified Assembly line.	5

Table 7-4 Comparative Test Data

Attribute / Test	Site 1 - Operator/Co-ordinator Comment & Contemporary System Results	Site 2 - Operator/Co-ordinator Comment & NGCS Framework System Results
System Flexibility - Add an additional discrete motion step to the test rig program including diagnostics.	A total of three hours were required to design the code, implement and modify the diagnostics. A high level of skill and knowledge was required throughout the process. The process was not considered to be intuitive and may be difficult to accomplish if not practised regularly. [3 hours]	Elements of the design and implementation of the additional step were considered to be more intuitive and user friendly than that seen on contemporary shop floor control systems. Examples include initial step *type* configuration and the designation of diagnostic messages. The process of defining a new step required several actions that appeared out of character with the process needed to define the initial part of step. Examples include the manual modification of function block parameters (to increase the range of sequential moves) and the use of IEC1131 code to define standard flags for use by the background function blocks. [2 hours]
System Flexibility - Delete a discrete motion step to the test rig program including diagnostics.	Disabling the discrete step from the sequence was relatively quick and easy. A more difficult task was to remove the code and diagnostics. Operator comment was that they would normally disable step not remove. [1 hour]	Easy to identify the correct step to be removed. Code and diagnostic message able to be removed cleanly. [30 minutes]
System Flexibility - Add forty additional input and output points.	The benefits of a proprietary system were not seen as the test rig utilised 3rd party Interbus I/O. A method statement from Siemens and subsequent evaluation by the training staff was used for the evaluation. The addition of a new input/output block to the Interbus network was achieved in 1 hour. Result taken from proprietary I/O. [30 minutes]	The NGCS system uses an *open* input/output interface as standard. Configuration tool was found to be user friendly but reasonably time consuming. [1 hour]

Attribute / Test	Site 1 - Operator/Co-ordinator Comment & Contemporary System Results	Site 2 - Operator/Co-ordinator Comment & NGCS Framework System Results
System Flexibility - Increase the main logic processor speed by 20%. Reload program and operate rig.	The Siemens processor fitted to the rig was an S5-115/944 processor. An upgrade to the 945 processor gave the required improvement. Note speed measured using scan time. It was noted that no further upgrade was available. [30min]	The RFC controller (Tier 5 & 6) uses a Motorola processor and could not be upgraded without a new design. The rig software program was recompiled from Motorola™ to Intel™. Once recompiled the rig run satisfactorily. It was noted that the BPC3 controller (Tier 3 & 4) was fitted with an Intel™ 486 giving the opportunity for further upgrade if required. [30 min]
System Agility - Configure test systems for 40 additional 3rd party input / output points.	The well established Siemens S5 range can be fitted with a number of serial interface cards allowing connection to many Industrial Actuator Sensor Bus systems. The rig was already fitted with an Interbus S adapter card manufactured by Phoenix. [1 hour]	The NGCS system uses an 'open' input/output interface as standard. Configuration tool was found to be user friendly but reasonably time consuming. [1 hour]
System Agility -.Addition of 3rd party motion functionality.	Relatively crude interface to third party system available via serial sensor actuator bus or RCM card (analogue +/- 10v). No connection via SERCOS available. No 3rd party interface boards. [Not Possible]	The operators were aware that 3rd party drives could be connected via SERCOS to the BPC3 (Tier 3, 4) controller however did not feel able to accomplish the task. Method statement from Krause and subsequent analysis revealed an estimated time of 4 hours. The skill level required to set drive parameters was considered too high for the majority of multi-skilled operators. [4 hours]
System Agility -change real time software manufacturer used for the sequential code and write one simple motion step.	The S5 is a proprietary system. Siemens confirmed that no 3rd party software is available to run on the S5 range. [Not Possible]	The RFC (tier 5, 6) controller could in theory be loaded with a third party system however no system was available at the time of the test. The Intel based system (BPC3) was loaded with Teledenken software. The system closely emulated the Allen Bradley style of programming. Few problems occurred in the loading of the new software however a new bus interface driver had to be written by Teledenken. (time required 2 weeks). Following delivery of the driver the system operated satisfactorily. Note test time assumes driver was available, Test completed by training staff not operators. [6 hours]

Attribute / Test	Site 1 -Contemporary System Results Summary	Site 2 - NGCS Framework System Results Summary
Operational Efficiency - Training Time required to train a multi-skilled operator to carry out specified maintenance actions and restart the machine cycle. Change processor, change power supply, change I/O point, change serial bus card, update an operator message, update a motion feed position.	All times agreed with training instructor based on Siemens/Krause recommendation and practical experience. Change of KAST (tier 6 processor) [30 min] S5 Processor change (tier 3,4,5) [120 mins] Machine power supply [60 mins] Change input/output block [20 mins] Change serial bus card [120 mins] Update of operator message [120 mins] It was noted that all tasks were designed to be achieved by skilled staff. **Total [350 mins]** **Total Training days/difficulty to complete all courses:** **Operator = 35/30** **Skilled trade = 27**	All times agreed with training instructor based on Control Supplier/Krause recommendation and practical experience. Change of RFC (tier 6, 5 processor)[15 min] BPC3 (tier 3,4) Processor change [120 mins] Machine power supply [15 mins] Change input/output block [20 mins] Change serial bus card [N/A] Update of operator message [60 mins] Note: Serial bus training contained in RFC/BPC3 training. **Total [230 mins]** All tasks except the update of operator messages was able to be achieved by a multi-skilled operator **Total Training days/difficulty to complete all courses:** **Operator = 21/18** **Skilled trade = 24**
Operational Efficiency - Diagnostic :Ability of the system to provide system (hardware) faults. Serial bus failure, memory error / loss, processor failure.	Serial bus failure - detected? - [Yes] Memory loss - detected? - [Yes] Processor failure - detected? - [Yes]	Serial bus failure - detected? - [Yes] Memory loss - detected? - [Yes] Processor failure - detected? - [Yes] The diagnostic indicators were available externally in all cases allowing multi-skilled operators to react to faults.
Operational Efficiency - Diagnostic Ability of the system to provide machine process faults. Short circuit protection 9input and output), Switch . failure, pairs check (both switches made).	Short circuit protection - detected? - [Yes] Pairs check - detected? - [Yes] Short circuit protection was only available at the I/O module. Upgrade to Interbus Loop™ would have provided identical functionality to NGCS. (i.e. short circuit to bit level sent via bus back to processor.) Pairs check is function of software programming not hardware.	Short circuit protection - detected? - [Yes] Pairs check - detected? - [Yes] Short circuit identified to bit level. Transmitted to processor via network and displayed on operator interface. Pairs check is function of software programming not hardware.

Attribute / Test	Site 1 - Operator/Co-ordinator Comment & Contemporary System Results	Site 2 - Operator/Co-ordinator Comment & NGCS Framework System Results
Scalability - The scalability of each system is measured by analysing the control system functionality and mapping it against each tier requirement profile. Functionality was gauged by identifying the minimum system functionality. Note: The adjacent diagrams are intended to illustrate in general terms, the points that different systems deviate from the *ideal* profile and are not intended to give a detailed representation of system functionality. The ideal profile is when Control System Functionality matches Functional requirements at any point in the tier structure.		
Availability - A measure of the % of time which a system is in an operable state at any point in time. Specifically , the percentage of time that the machinery will be operable when needed. [SAE 1993]	The existing model was run using mean time between failure (MTBF)and mean time to repair (MTTR) data collected from an existing Assembly line [Zetec S.E. Valencia Engine Plant, Ford Motor Company]. It was assumed that the reliability (MTBF) of the Contemporary and NGCS systems were comparable. Average output per shift = 836	The MTTR was varied based upon tests carried out to measure the time required to exchange the NGCS. All faults below 4 minutes remained constant as the NGCS design is assumed to have little effect on the diagnosis or speed of change of minor mechanical and sensor actuator faults. Average output per shift = 874 4.6% Improvement over base.

Attribute / Test	Site 1 - Operator/Co-ordinator Comment & Contemporary System Results	Site 2 - Operator/Co-ordinator Comment & NGCS Framework System Results
Accuracy / Performance - The average cyclical scan time of a machine controller.	Scan test carried out on a Jaguar engine assembly machine used to check collet alignment. Results represent average scan value over ten machine cycles. First test run with Siemens S5-952 processor. Second test value with S5-945 processor. Machine software identical for both runs. [58ms], [12ms]	Scan test carried out on same site 1 machine using 486 PC based controller (similar hardware to that used on site 2). All external hardware remained constant (i.e. linked to controller via serial sensor actuator bus). Real time controller Phoenix PC Worx™. Sequence of operation identical. Original program structure emulated wherever possible. Result represents average scan value over ten machine cycles. [12ms]
Purchase Cost - *The purchase cost of the main controller elements given a typical line quantity for each tier group.* Notes All prices in German DM Typical Assembly line tier quantity as follows: Tier 6 = 30 Tier 5 = 30 Tier 4 = 40 Tier 3 = 10	Tier 6 Equivalent 1900 DM Tier 5 Equivalent 11682 DM Tier 4 Equivalent 13505 DM Tier 3 Equivalent 13505 DM **Total Assembly Line Cost = 1352810 DM**	Tier 6 3000 DM Tier 5 3400 DM Tier 4 8200 DM Tier 3 8490 DM **Total Assembly Line Cost = 604900 DM**

7.5 Comparative Test Analysis

7.5.1 System Flexibility

The *System Flexibility* evaluation criterion assumes that the manufacturing control system was originally selected to encompass all known and planned machine functionality. Therefore the measure of a systems flexibility is taken to be its ability to be modified and reconfigured using equipment from the original manufacturer.

Measured improvements were seen in the modification of the sequential control software. The use of structured dialogue boxes to collect process data proved to be an effective tool when working with multi-skilled staff. A limiting factor was the final stages of the step definition, which at the time of the tests required IEC1131 code to be written. No measurable improvement was seen in the time to add additional hardware or to upgrade processing speed. The contemporary test system utilised a similar sensor actuator system to that used on the NGCS system. Greater benefit would have been seen if the NGCS system had been compared to a contemporary system using a rack mounted input / output system. The test identified that redundant code is often left in existing programs due to the complexity (and risk felt by the operator) of removing it. The study concluded that the NGCS system gave a 9% improvement over a contemporary system.

7.5.2 System Agility

The *System Agility* attribute measured the ability of a the system to rapidly adapt to unforeseen change, therefore, the measure of a system's flexibility is taken to be its ability to be reconfigured with third party products.

The *open* architecture of the NGCS system revealed major benefits in this test. The contemporary system was restricted to connecting to third party systems via the sensor actuator bus interface. In contrast the NGCS system gave the potential to fully integrate third party products. The contemporary controller was restricted to the original manufacturers real time code and hence programming environment. Two different real time systems with different real time engines were successfully tested on the NGCS system were used on the NGCS controller.

7.5.3 Operational Efficiency

Operational Efficiency is defined as the ability of an advanced manufacturing technology to integrate with its operating environment.

The NGCS's modular construction, use of quick-change connectors and software units with the ability to automatically download, realised a major reduction in required training (66%) to achieve the specified tasks. Of the six tasks specified it was judged that a multi-skilled operator could accomplish five. The team carrying out the tests judged that all tasks on the contemporary system would require a skilled maintenance person.

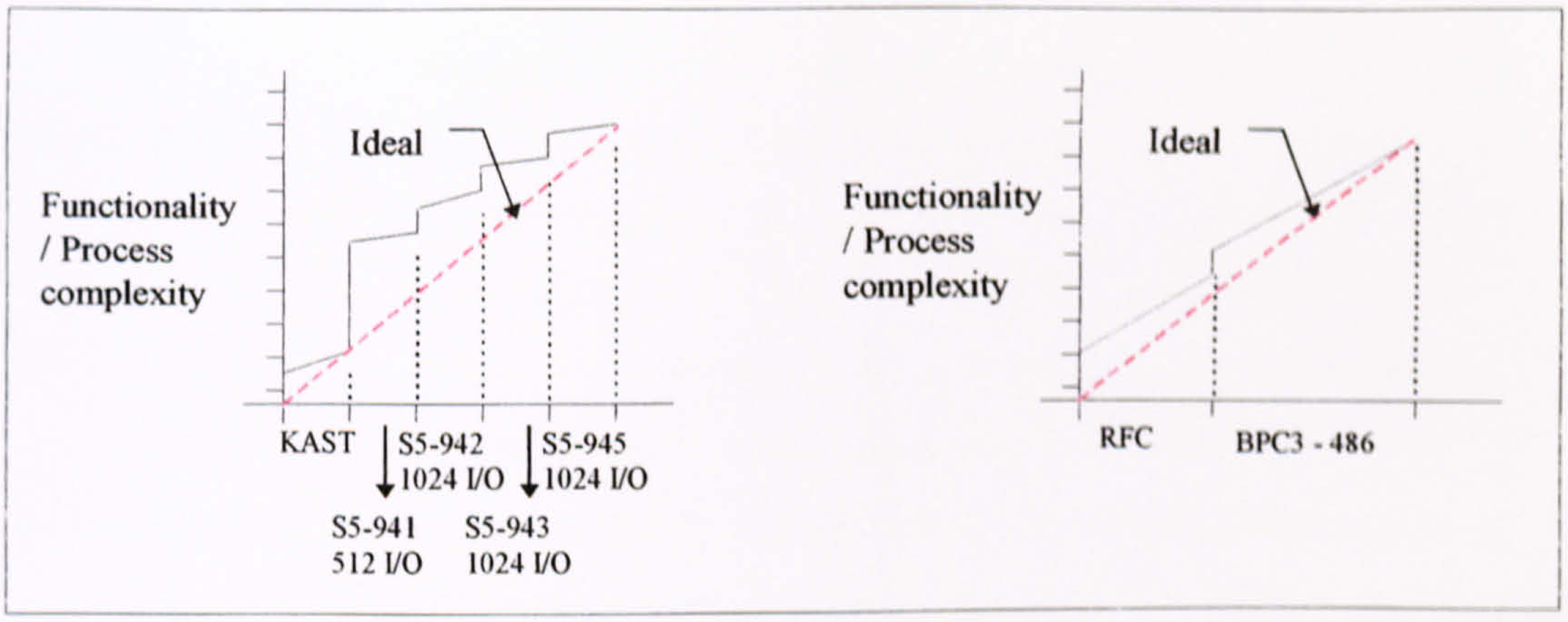
The NGCS Framework draws attention to the need for effective diagnostics. Testing revealed that both systems provided a high degree of effectiveness in identifying process and hardware faults. The effectiveness of the systems to diagnose process faults is a function of the software design, hence the results may vary greatly with different software structures. The NGCS software displayed a greater degree of in-built structure reducing potential variability in this area.

7.5.4 Scalability

The scalability attribute was defined as the ability of a system to match process functionality (and hence complexity) with control functionality. Ten functional increments representative of the operating environment were mapped against the available control configuration.

The contemporary system under test utilised a pre-configured 'shoebox' style controller for the conveyor applications. Whilst matching functionality efficiently at this point the controller could only be used for tier 6 applications. This limitation led to the step increase shown in Figure 7-1 below. The NGCS controller used for Tier 6 applications displays a higher base functionality however the controller is able to extend to tier 5 and (subject to the operator interface requirements) some tier 4 applications.

Figure 7-1 Scalability Comparison



7.5.5 Availability

A *Witness* Simulation was considered by the author to provide a more realistic assessment of potential improvement than the traditional MTTR and MTBF calculations based upon individual system elements. The model of the contemporary system had been verified against actual plant data over a period of two years. The breakdown history (duration and frequency) was also validated against field data taken from Ford Motor Company's Valencia Engine Plant. The quick change and quick load facilities evident on the NGCS design improved changeover and reload times to 4 minutes for the larger units and two minutes for the motor controllers and smaller controller. The author considers the 4.6% improvement to be conservative as all electrical repair times were set at four minutes on the NGCS system.

7.5.6 Technical Performance

The Technical performance attribute was taken as the average cyclical scan time of a comparative machine controller. The test results revealed that both systems produced comparable results.

7.5.7 Purchase Cost

Purchase cost is defined as the purchase cost of the main controller elements given a typical line quantity for each tier group. The S.E. team apportioned a relatively low *weighting factor* to this test element however the improvement shown by the NGCS is significant. The author feels that the results must be treated with caution, as initial applications of the NGCS will be associated with significant development work that will reduce or eliminate the benefit seen. Although the Tier 6 application was more expensive its wider application base generates savings at Tier 5.

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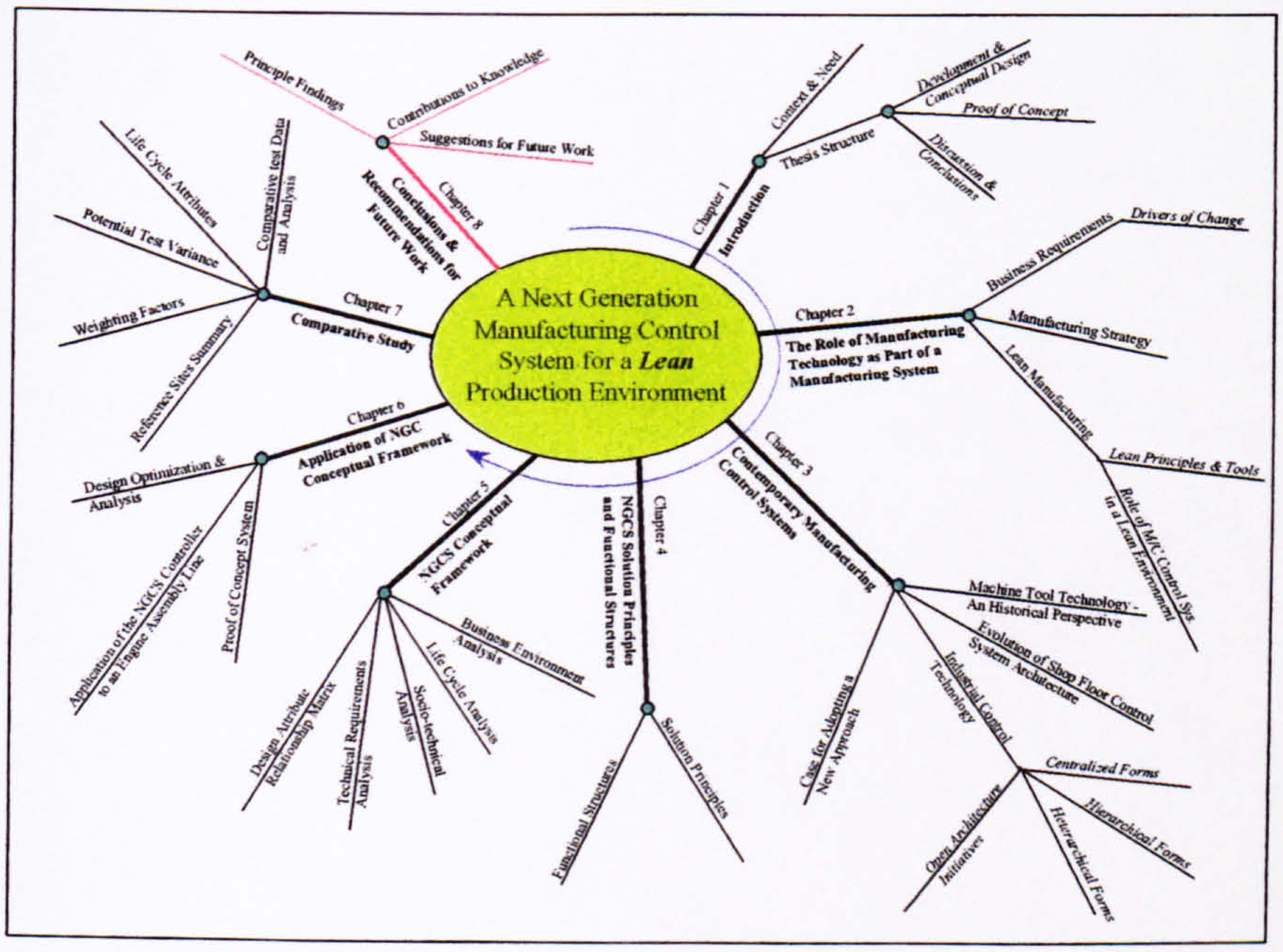
CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK



8. Conclusions and Recommendations for Future Work

8.1 Introduction

The aim of this chapter is to summarise the major elements of the work carried out in this thesis and discusses the principle findings with regard to the literature surveyed, concepts presented and NGCS Framework implementation and testing. Major contributions to knowledge are listed, highlighting areas where these contributions have satisfied the stated aims and objectives. The chapter concludes with suggestions for further research.

8.2 Major Elements of Work

This thesis focuses on addressing the need for a new approach to the design and implementation of manufacturing control systems for the automotive industry and in particular for high volume engine manufacture. Whilst the operational domain in the automotive industry has moved to *lean production* techniques, the design of present-day manufacturing control systems is still based on systems intended for use in a *mass production* environment. The design and implementation of current manufacturing control systems is therefore inappropriate when viewed from a business context. The author proposes that it is possible to create a more appropriate manufacturing control systems based on an optimised use of advanced manufacturing technology within the complete business context.

Literature is reviewed to provide a detailed understanding of the relationship between modern operating practices and the application of contemporary control systems. The primary tasks of manufacturing control systems, within the context of a structured systems approach to manufacturing technology, production management and industrial economics are identified. A study of modern manufacturing control system technology is carried out, highlighting the fundamental principles that influence application engineering in this area.

The thesis develops a conceptual design framework that aids the identification of attributes required of a next generation manufacturing control system (NGCS), in order to enhance the business performance of *lean* automotive manufacturing. The architecture for a next generation control system is specified and a *proof of concept* system implemented. Potential advances over contemporary practice are identified with the aid of a practical implementation at a major automotive manufacturer. A comparative study between the NGCS and a conventional system is described. Testing carried out at two reference sites is described and a method for weighting different factors explained. Test results are discussed and potential test variances highlighted.

8.3 Principle Findings

The study and characterisation of contemporary manufacturing strategies and technology is essential if a new design framework is to produce a control system that meets the needs of a *lean manufacturing* environment. Section 2.3 identifies the birthplace of the modern manufacturing era as Henry Ford's manufacturing model. Many of the *lean* principles evident in modern systems can be found in Ford's original factories however, in an attempt to meet the demands of a rapidly expanding market; Ford's principles of synchronous production flow and waste elimination were lost. The *mass production* principles that replaced them resulted in a misguided attempt to isolate the manufacturing system from outside demands and pressures. The Japanese adapted Ford's original principles to meet their particular market requirements and in doing so produced a more effective production system.

The author concludes from the study of advanced manufacturing systems in Section 2.2 that the establishment of Japanese manufacturing facilities in Europe and North America and key alliances between Japanese and W*estern* automotive companies has resulted in the elimination of *mass production* techniques and by doing so has effectively globalised manufacturing strategy in the high volume automotive sector. This globalisation of manufacturing strategy provides a common set of user requirements upon which Advanced manufacturing Technology (AMT) providers can focus.

The study of contemporary industrial control in Chapter 3 identifies a bewildering array of technical solutions and diversity of opinion as to which of the available technologies is best suited to an application. Four architectural forms are identified namely: centralised, proper hierarchical, modified hierarchical and Heterarchical. The author concludes from the application of the NGCS Design Framework that despite the Automotive industry being instrumental in the development of the first programmable logic controllers, a *gap* has formed between contemporary Automotive manufacturing requirements and available application technology.

To operate as effectively as possible end users have used various methods to minimise the effect of this *gap*. The author proposes that these methods can be broadly characterised by region. In Europe this has been achieved by increasing the level of support from technology providers. Japanese end users have dealt with this issue by employing simpler systems with lower levels of automation and compensated for the technology they must employ (to maintain quality) by using highly skilled shop-floor technicians. In North America a strong unionised labour force has maintained the division of skilled labour and resisted more efficient multi-skilled working practices.

The author's survey of contemporary manufacturing literature identifies three principle areas where AMT has traditionally played a major role in supporting manufacturing strategy, namely: life cycle cost, providing flexible and agile production facilities and sustaining continuous improvement. The results of the Sociotechnical Model analysis presented in section 5.2 and subsequent experience from the application of the Framework in chapter 6 leads the author to believe that in a *lean* manufacturing environment AMT also plays a significant role in supporting the organisation and effectiveness of labour. Section 2.6 recognises the neglect of social and organisational issues as one of the principle causes of inadequately functioning systems and proposes the necessity for greater co-operation between social and technical elements in the design of AMT systems. The NGCS design framework described in section 4.2 proposes a sociotechnical analysis as one of the principle methods of addressing this issue. Test results in chapter 7 show that where the design attributes resulting from the NGCS Design Framework were implemented, measurable benefit was seen.

Effective shop floor control systems are combinations of production resources, information and manufacturing technology and human resources. The analysis of manufacturing systems in Chapter 2 and contemporary systems in Chapter 3 reveals that most research focuses on the automated control system and their relation with the production equipment. The author believes that future excellence in control system design will be achieved by advanced manufacturing technology providers combining detailed technical knowledge with a greater understanding of the end user's operational strategy. Involvement will extend to an intrinsic understanding of the end users product and manufacturing strategy in terms of volume, line flexibility, current and future derivatives and operating practice. The AMT will align product development and the release of new technologies to meet end users requirements.

Chapter 4 highlights the importance of architectures and design frameworks as an essential tool to aid the understanding and development of AMT systems. The author proposes that the NGCS Framework presented in this thesis, guides the designer from a highly abstract Business and Life Cycle domain analysis through Socio-technical and Technical design and development stages, resulting in NGCS Reference Architecture and suitable application technology. The author recognises a number of architecting concepts that enable the designer to mange overall system complexity, namely:

- domains or environments can be used to highlight and define areas that must be considered. The NGCS Framework identifies four domains, Business, Life-Cycle, Sociotechnical and Technical.
- definitions are required, that allow the discussion and development of a clear set of criteria and requirements,
- hierarchical decomposition and tier structures should be used to divide systems into a number of sub-systems. The complexity of each sub-system is more manageable than that of the original system.
- views can be used to emphasis particular aspects of a design allowing the designer to focus on a particular aspect of the design.
- technical design methods must be utilised that manage complexity and facilitate modular, stable designs with inherent structural stability,
- the design should proceed within an environment that simultaneously refines the design in the functional and technology domain to promote the symbiosis of technology and human activity.
- attention must be paid to processes that monitor and feedback design output performance and address imperfections.

Future manufacturing excellence will be characterised by end user and AMT suppliers that accept the definition that AMT is introduced not only for its economic benefits but also for its ability to allow the organisation to use manufacturing as a strategic weapon. AMT design and implementation must take into account manufacturing strategy at every stage of the design and development. The author concludes that *lean* manufacturing requires a change in the engineering orientation from the dominance of technical issues in shop-floor control system design to those of work organisation.

8.4 Contributions to Knowledge

The author believes that this work has contributed to knowledge in the following areas:

The author proposes that the NGCS Design Framework provides a contribution to the development of Next Generation Manufacturing Control Systems. The NGCS Design Framework created as part of this study, supports the design, development and application of advanced manufacturing technology for a *lean* operating environment. The viability of the design has been tested and shown to provide a more effective solution.

Providing a Strategy for Dealing with Legacy Operations: In the design and development of shop-floor control systems little attention is paid to the requirements of the legacy workforce or manufacturing facility. Research to date has focused on installing or training a new workforce able to cope with the installed technology. The work in this thesis challenges the view that this is the only method of raising equipment availability in a multi-skilled environment.

Providing a Novel Design Framework that Specifically Addresses Socio-technical Issues Found in a lean Manufacturing Environment: Most research focuses on the automated control systems and their relation with the production equipment. This thesis considers the role of the human and challenges current assumptions concerning the design of manufacturing control systems. This work also contributes by highlighting control elements that improve manufacturing performance and yet have been largely ignored by previous research.

Defining the Concept of Active Filters to Assess Design Effectiveness: The author identifies three conceptual *active filters* namely,: cost, quality and time. The aim of the *active filters* is to compensate for flawed control system design. The author proposes, that by specifically focussing on minimisation of end user fixes, design effectiveness is enhanced.

The Application of a Design Attribute Relationship Matrix to Link Shopfloor Control System Design Attributes to the Manufacturing Strategy: The author introduces the concept of a 'Design Attribute Relationship Matrix' (DARM) with the aim of providing clarification and a linked relationship between manufacturing strategy and design attributes. The interconnecting matrixes highlight to the various stakeholders in the design process the relationship between the key business, lifecycle, socio-technical and technical design factors, and promote a method of forward and backward propagation between them. The DARM may be used not only to record initial design decisions, but also to assess the potential impact of requested changes to the system.

The Development of a Comparative Test Method to Assess the Effectiveness of a Shop-floor Control System Design: This work has contributed toward the development of a quantitative measure of technical and operational performance between a contemporary control system and the NGCS Controller. Factors influencing the life cycle effectiveness of the systems are consolidated into seven evaluation criteria, namely: system flexibility, agility, operational efficiency, scalability, availability, performance and cost. A *weighting factor* is introduced to distinguish the importance of each criteria to the overall system performance. The test and measurement method is given and where possible a quantitative scaling system used to present the results.

8.5 Suggestions for Future Work

The research and application of an NGCS design framework reveals two categories into which future work may be placed. The first set of issues are those which, although an issue in the current implementation, will be resolved via natural product development and hence do not require specific further research. Examples of these are: product gaps evident in the serial bus system (causing a second bus to be used) and servo hardware issues, which bring about additional complexity. Issues from the second category that requires further research are:

Wider Application of the NGCS Design Framework.
The initial application of the NGCS Design Framework focused on an Engine Assembly Line application. At the time of writing the author is aware of on-going research and development to identify the suitability of the design framework to machining applications in the Automotive Industry. Further research is required to understand the benefits and implications of applying the framework to a wider domain including continuous process industry.

Application of the NGCS Framework Principles to a 'Heterarchical' system. It is the author's view that Heterarchical Systems represent the next logical *architectural* step in manufacturing control system design. As such further research is needed to apply the framework to this type of architecture.

A Reference Model is required for a Process Development Language and an Integrated Programming and Diagnostic Environment.
The software concepts and principles realised on the Puma Assembly Line represent an initial attempt at defining an integrated programming, diagnostic and monitoring environment. Two areas require significant research effort, namely: the development of a reference model for Process Development Languages (as opposed to sequential control software) and a model for the integration of motion control and device bus systems into an integrated programming environment.

Socio-technical Attribute Modification

The model used to identify and align socio-technical issues requires further work to reflect the principles formulated in this dissertation. Particular attention should be paid to the complex interaction between skill alignment and technology attributes. The current model considers these areas separately.

Long term evaluation of the NGCS Implementation at Ford.

Following a period of stable high volume production a detailed field study would provide a greater insight into the effectiveness of the NGCS principles on a *lean* manufacturing Environment.

APPENDIX A

OPEN CONTROL RESEARCH PROJECTS

A1.1 Research Projects Related to Open Control

Research Group and Project Focus	Details
TEAM (Technologies Enabling Agile Manufacturing)	This US the government sponsored project has a working group developing a specification that defines an intelligent closed loop controller environment to support open architecture concepts including application portability at the source level, interoperability of modules, and extensibility of controller functionality. The ICLP (Intelligent Closed Loop Processing) area within the TEAM project is addressing manufacturing control issues. One key research task of the TEAM ICLP project is to develop a draft/preliminary set of common Application Programming Interfaces (APIs).
ICON Manufacturing Operating System Project	One of the major objectives of the ICON project (which is funded by the US Department of Energy) is to develop a real time operating system infrastructure, called the Manufacturing Operating System (MOS), that also supports MS Windows. One of the deliverables of this project being developed in collaboration with GMPT is an OMAC running under MOS.
NIST/EMC (National Institute of Standards and Technology / Enhanced Machine Controller)	NIST has been working on technical issues related to control architecture for many years, and the objective of the EMC project is to implement a PC-based CNC controller based on the knowledge that has been developed within NIST. One important objective of the EMC project is development of a software wrapper (or API), which allows the capability of "Plug and Play" for a number of commercial motion control cards.
Title III Project for Open Architecture Machine Tool Controller	The objective of the Title III Project (funded by the US Department of Defence) is to establish an open architecture for a world class, US built machine tool controller and evaluate the benefits of the open system concept at different test sites. The goal is the commercialisation of an open architecture machine tool controller, for both defence and commercial applications.
GMPTG OMAC Pilot Programme	The Advanced Manufacturing Department of GM Powertrain and the Manufacturing Controls Department of the GM North American Operations (NAO) Manufacturing Centre have several active OMAC pilot projects. These projects are being done either as a part of the validation process or to support the government sponsored development efforts.

A1.1 Research Projects Related to Open Control (Continued)

Research Group and Project Focus	Details
RCS/ARTICS Architecture for Real-Time Intelligent Control Systems)	RCS was first implemented in the mid 1970s. RCS-3 became the NASA/NBS Standard Reference Model for tele-robot control systems architectures (NASREM). Systems based on RCS have been implemented for a variety of applications including: the NIST Automated Manufacturing Research Facility (AMRF), autonomous vehicles, submarine automation and coal-mining systems. In 1991 Albus et al. proposed a reference model (ARTICS), which would be defined through co-operative efforts of industry, academia and government. As envisaged, ARTICS would be a series of evolving guidelines specifying an infrastructure of hardware components, software components, communication protocols and application development tools.
MOSAIC (Europe) (Modular Open System Architecture for Industrial Motion Control)	MOSAIC was a European ESPRIT II research project. A consortium of twelve European companies and research groups were involved in this project that was of two years duration and ended in 1993. The Open Motion Control (OMC) architecture evolved on this project was designed to address applications such as handling equipment (including industrial robots), automatic vehicles (e.g. mobile autonomous robots) and special purpose systems (such as motion-oriented shop floor systems). Its primary focus was however fixed and mobile industrial robots. The OMC architecture is a fixed four-layer derivative of the NASREM model.
OSACA (Open System Architecture for Control within Automation Systems)	The main goal of the European ESPRIT III project OSACA is the definition of hardware independent reference architecture for numerical controllers, robot controllers, programmable logic controllers and cell controllers. The project, which started in May 1992 with a duration of 3 years, is looking primarily at machine tools. With a stated investment of ECU 12 million, OSACA claimed to be the largest such research initiative in the world.
OSEC	The OSEC group in Japan,
C^2RM (Command and Control Reference Model)	The C^2RM was developed for autonomous underwater vehicles used in navel applications. However, Harris and Fraser propose that it is applicable to many application domains including manufacturing automation and distributed intelligent systems. C^2RM again uses a reference model derived from the NIST NASREM architecture and was adopted for the European mobile robots project PANORAMA.

A1.1 Research Projects Related to Open Control (Continued)

Research Group and Project Focus	Details
MOSAIC (US) (Machine-tool Open System Architecture Intelligent Control)	MOSAIC was a US research project. It is a "software architecture that permits introduction of new sensors, hardware, and processing algorithms, so as to increase the utility of machine tools". The Defence Advanced Research Project Agency (DARPA) funded the MOSAIC research project. MOSAIC has been designed to be reconfigurable, allowing new axes of motion or new sensors to be easily added to a machine.
NGC (Next Generation workstation/machine Controller)	The NGC research programme was set up in the US in1989. It was intended that the project would be driven by industry but this was never achieved and the US Air Force and the National Centre for Manufacturing Sciences (NCMS) stepped in to guide the initiative. The four-year programme (budgeted at $19.1 million) aimed to produce an open system architecture standard for machine tools. NIST have been closely involved in specifying the NGC system architecture and that it has been influenced by their RCS research.
UMC/IMDC	The Manufacturing Systems Integration (MSI) Research Institute at Loughborough University has carried out research into new approaches to machine control funded by the UK government. It has resulted in UMC (Universal Machine Control), which is an approach to creating open control systems for a diverse range of applications. A major main focus of this work was special purpose machines for packaging and printing applications. The latest phase of this research is IMDC (Integrated Machine Design and Control). IMDC features a distributed runtime architecture that is utilising Fieldbus technology. The IMDC platform is adopting an approach, which closely integrates the real-time control system with machine design (and other off-line lifecycle activities).

APPENDIX B

LIFE CYCLE COSTING MODEL

B1.1 Introduction

The following pages represent a typical Life Cycle Analysis tool used for machine tools and equipment. The analysis tool shown is Copyright of the Ford Motor Company Limited.

All formulas to produce the calculated totals are considered proprietary information by the Ford motor Company and as such have been removed from the worksheets.

All figures are examples only and cannot be taken to reflect expected figures.

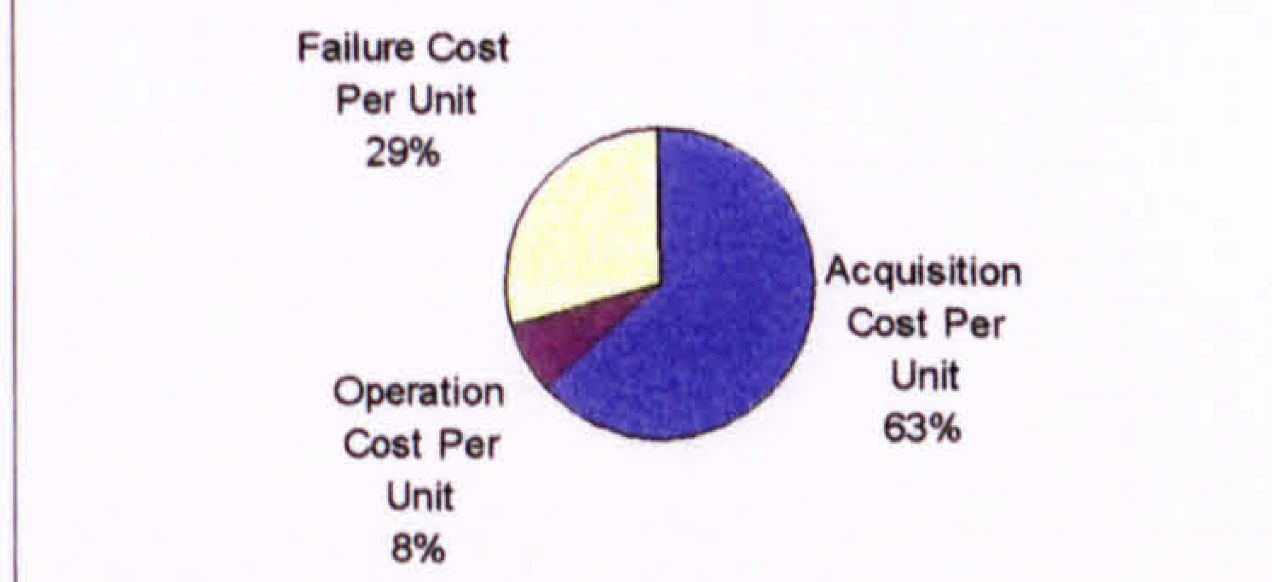
MACHINERY LIFE CYCLE COST ANALYSIS - DATA INPUT SHEET			
STANDARD PARAMETERS	Cost in $	**ACQUISITION COST PER MACHINE**	Cost in $
Production Quantity Required (Parts/Year)		Purchase Price	
Inventory Carrying Cost % per Year		Administration/Engineering	
Floor and Foundation Cost per Square Foot		Machine Development	
Electricity Cost per KWHr.		Initial Spares	
Shipping Cost per Pound		Warranty	
Training Cost per Hour		Conversion	
Maintenance Cost per Hour		Decommission	
Inflation Rate		Support Equipment - Hardware	
Total hours worked per week		Support Equipment - Software	
Total weeks worked per year		Installation	
Life of equipment (years)		Miscellaneous Acquisition Costs	
		Facility Cost	
MACHINE SPECIFIC PARAMETERS		Training Cost	
Production Rate (per hour)		Shipping Cost	
Weight of Machine (lbs.)		**TOTAL ACQUISITION COST**	
Footprint of Each Machine (Sq. Ft.)			
Training Hours Required (per machine)		**OPERATION COSTS (PER OPERATION HOUR)**	
Preventive Maintenance Hrs/Year		Changeover	
Predictive Maintenance Hrs/Year		Operator(s)	
Tool Life (Parts/Tool)		Tooling	
Tool Set Cost		Adjustment	
Lubricant Cost per Year		Misc. Consumables	
Coolant Fluid Cost per Year		Other operation costs	
Machine Electricity Consumption (KW/Hr.)		Electricity	
Miscellaneous Consumables Cost per Year		Lubrication	
Warranty Length (Years)		Coolant Fluid	
Machine Yield (%)		Preventive & Predictive Maintenance	
Mean Time to Re-tool (Hrs.)		**TOTAL OPERATION COST (PER OPERATION HOUR)**	
Non Spared Items Requiring Major Rework			
Major Rework Turn Around Time (week)		**DOWNTIME COSTS (PER HOUR)**	
No. of Machines Required to Meet Production		Repair technician hourly rate*	

No. of Machines Required to Meet Production (rounded)		General downtime cost per hour	
Number of Units Produced Over Life/Machine		**TOTAL DOWNTIME COST (PER OPERATION HOUR)**	

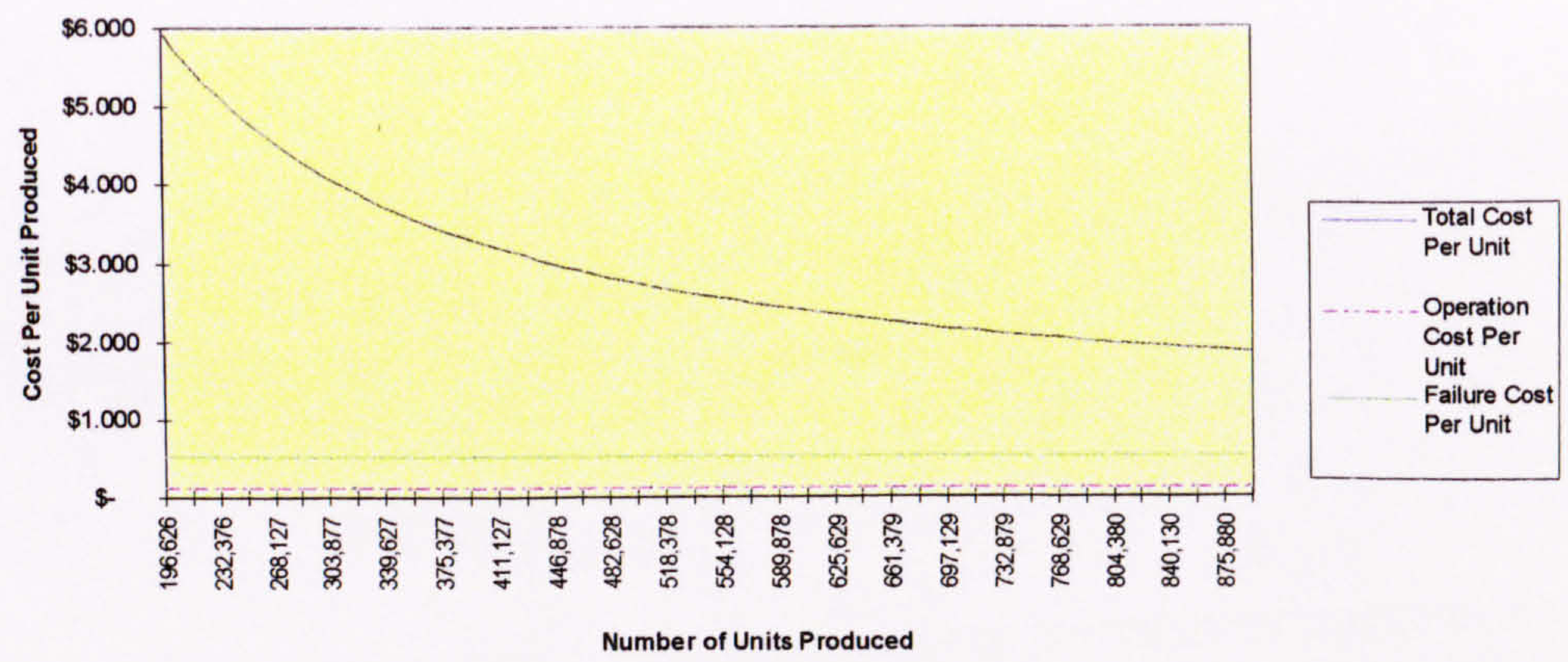
MACHINERY LIFE CYCLE COST ANALYSIS - FAILURE MODE ANALYSIS SHEET

Total Life Cycle Cost per Unit	$ ______
Availability	98.2 %
Overall MTBF	46.8 HRS
Overall MTTR	0.27 HRS
Production Rate Effective Production Rate	16 per Hour 15.27 per Hour
Operations Cost per Unit	$ ______
Failure cost per Unit	$ ______
Acquisition Cost per Unit	$ ______
10 YEAR OWNERSHIP ANALYSIS	
10 YEAR MAINTENANCE TOTAL	$ ______
10 Year Maintenance Actions	$ ______
10 Year Corrective Maintenance Labor Cost	$ ______
10 Year Crisis Downtime Cost	$ ______
10 Year Preventive Maintenance Cost	$ ______
10 Year Predictive Maintenance Cost	$ ______
10 Year Major Rework Downtime Cost	$ ______
10Year Corrective Maintenance Labor Cost	$ ______
10 Year Crisis Downtime Cost	$ ______
10 Year Preventive Maintenance Cost	$ ______
10 Year Predictive Maintenance Cost	$ ______
10 Year Major Rework Downtime Cost	$ ______
10 YEAR INVENTORY MANAGEMENT	$ ______
10 YEAR CONSUMABLES TOTAL	$ ______
10 Year Tooling Set Cost	$ ______
10 Year Tool Change Maintenance Cost	$ ______
10 Year Machine Electricity Cost	$ ______
10 Year Lubrication Cost	$ ______
10 Year Coolant Cost	$ ______

Distribution of Failure Mode Costs



Distribution of Unit Costs Over Life



10 YEAR OWNERSHIP ANALYSIS	
10 YEAR OWNERSHIP COST	$ __A__
ACQUISITION COST	$ __B__

10 YEAR LIFE CYCLE COST	$ ___A+B__

APPENDIX C

NGCS/CONTEMPORARY CONTROL SYSTEM COMPARATIVE STUDY

C1.1 Introduction

This appendix describes research carried out by the author with the aim of developing a quantitative measure of improvement between a contemporary control system and the NGC Framework system applied to the Puma Assembly line. The study begins with a 'problem definition' followed by a summary of the two reference sites. Factors influencing the life cycle effectiveness of the systems are consolidated into seven evaluation criteria, namely: system flexibility, agility, operational efficiency, scalability, availability, performance and cost.

A 'weighting factor ' is introduced to distinguish the importance of each criteria. The weighting factors were established via a series of consensus-building meetings with an industry team representing machine tool builders and end users. An explanation of each criteria specifying the test and measurement method ensures consistency and where possible a quantitative scaling system is used.

C1.2 Problem Definition

The purpose of the comparative research study is:

1. To identify quantitative research criteria to determine the 'Life Cycle Value' of a control system when applied to an application in a lean manufacturing environment.
2. To use the research criteria to understand the benefits and weaknesses of the Puma Assembly system when compared to an assembly line using a contemporary control system architecture.
3. To recognise the strengths and weaknesses of the NGC Framework and identify areas requiring further work.

C1.3 Reference Sites

Table E 1 Site Summary Table

	Site 1 (Research date: 5/98)	Site 2 (Research date 10/98)
Location	Ford Motor Company Limited, Bridgend.	Ford Motor Company Limited, Dagenham.
Line	Zetec S.E.	Puma Engine
Product Complexity	Inline 4 cylinder, 16 valve gasoline.	Inline 4 cylinder, 16 valve diesel.
Equipment Job 1 date.	5/98	5/99
Production volume	550,000 engines per year	450,000 engines per year
Operating philosophy	Lean production methods. Team based multiskilled operators.	Lean production methods. Team based multiskilled operators.
Manufacturing Control System	Contemporary. Siemens PLC and pre-programmed KADESS modules on the conveyor system	NGC Framework Control System.

C1.4 Test Equipment

Funding for a new assembly line has in both site 1 and 2 included for a test and training rig which emulates the assembly line control system. Unless specifically stated comparative test were carried out on these rigs. The main system elements for each rig is shown in Figure C 1 and Figure C 2 below.

C1.5 Test Operators

The Ford staff used during the test were members of the respective site staff and had been trained on the equipment under test. Two multi-skilled operators worked jointly on the tasks that required operator involvement.

C1.6 Test Supervision

To ensure consistency between the sites the author employed a lecturer from the University of East Anglia to monitor both sets of tests. In addition Ford Training staff monitored the tests at their respective sites.

C1.7 Potential Test Variance

A number of test variance were noted:

1. The multi-skilled operators at site 1 appeared to be more experienced with the system. As well as formal training the two operators had spent several months working with on the production facility.
2. The operators at site 2 had just completed initial training. At the time of the test the site 2 production facility was not running hence no production experience had been gained.
3. Where the task could not be completed by the operators this is noted within the test results. The manufacturer of the equipment was asked for a method statement. A judgement was then made by the Ford training staff with regard to feasibility and time required. The two training staff may have judged the required time to be different. Note: Software training was carried out by the same instructor for both systems and sites therefore consistency is maintained for this criteria.
4. Accurate reliability data was available for the contemporary equipment via the Ford Production Monitoring and Failure systems. The NGC equipment had at the time of the tests not been used in production. MTBF for site 2 was therefore derived from manufacturer data sheet.

C1.8 Test Dates

- Site 1 - 5th May 1998 - 8th May 1998
- Site 2 - June 1998

Figure C 1 Site 1 Test Rig Configuration.

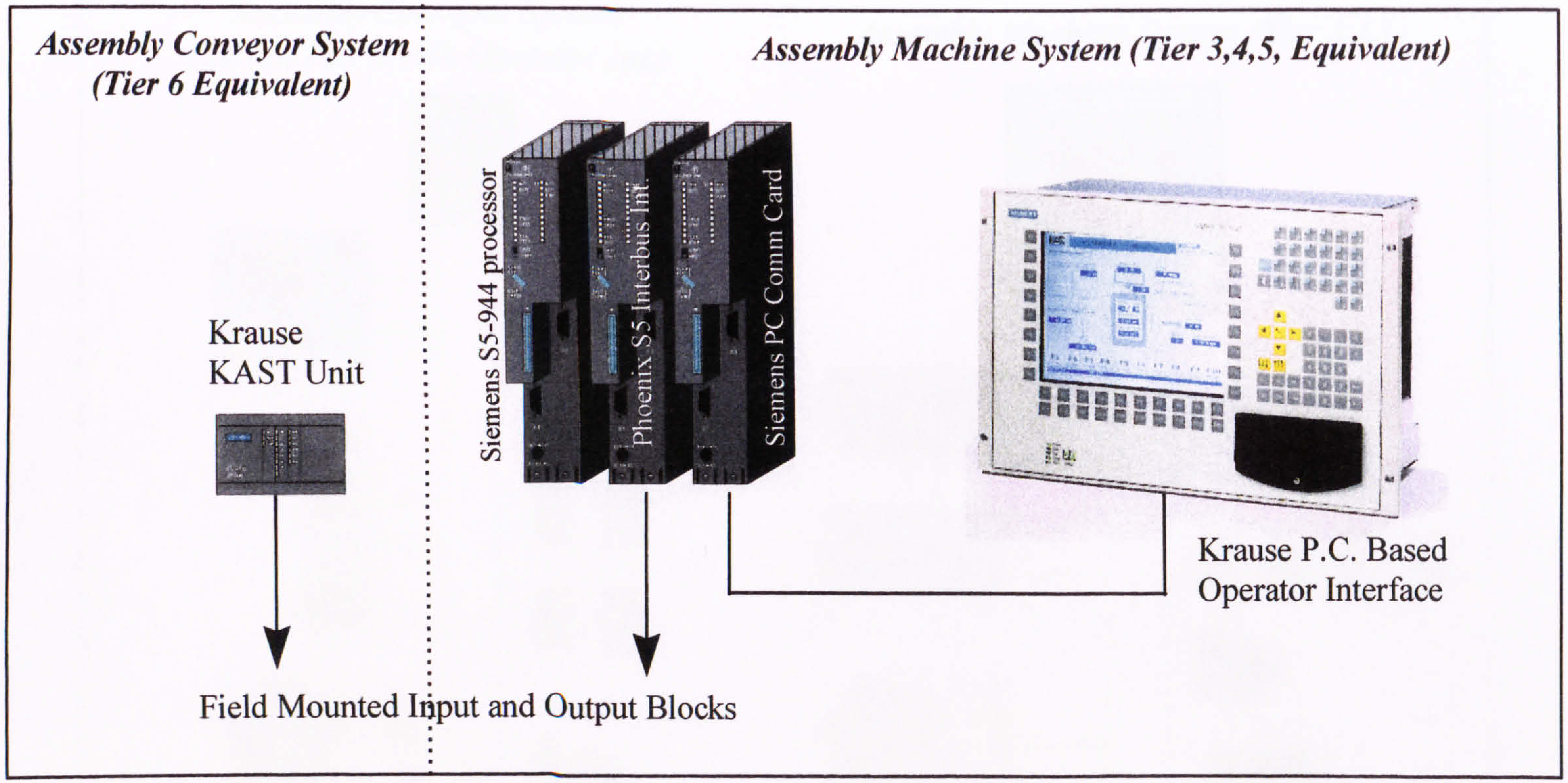
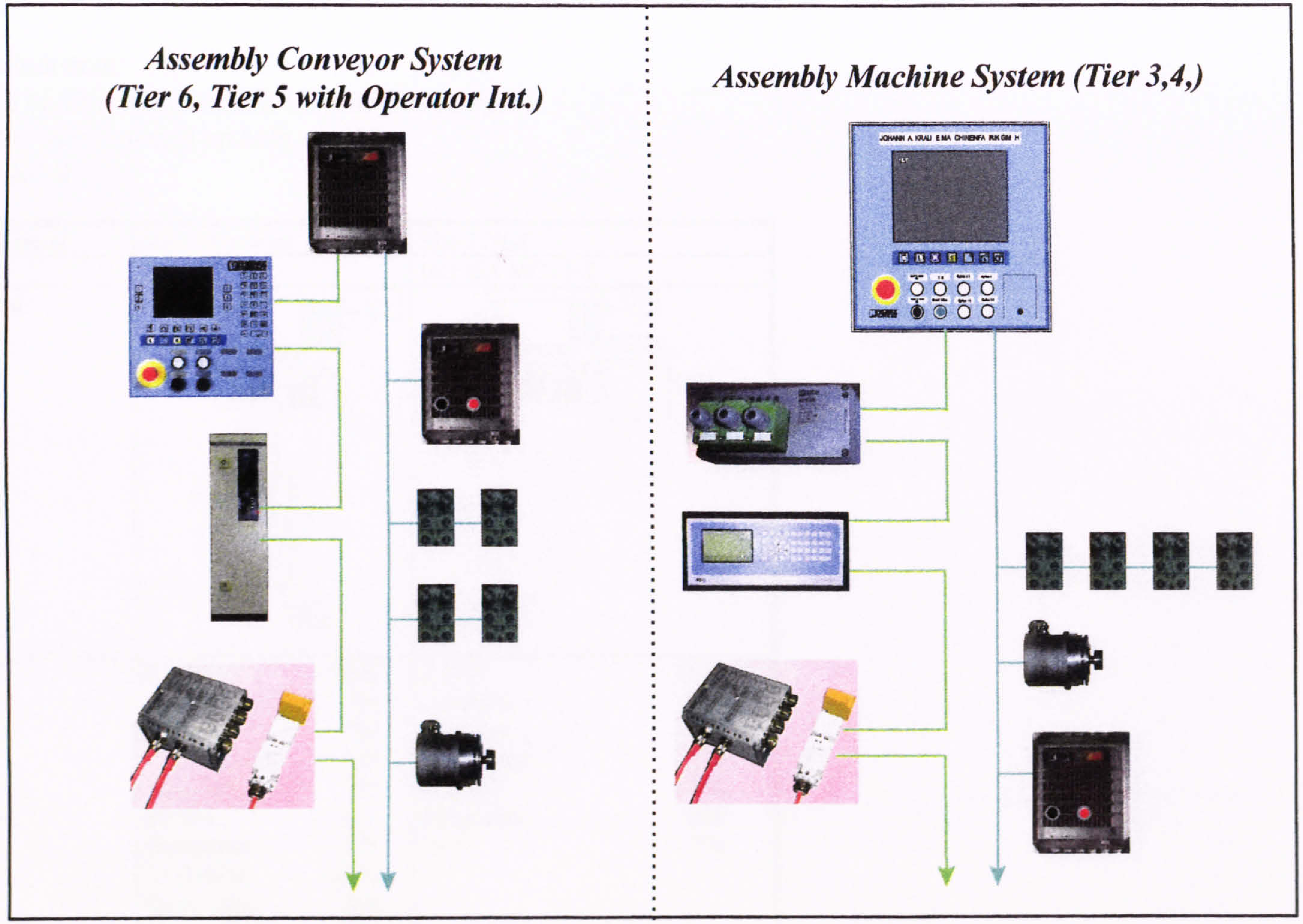


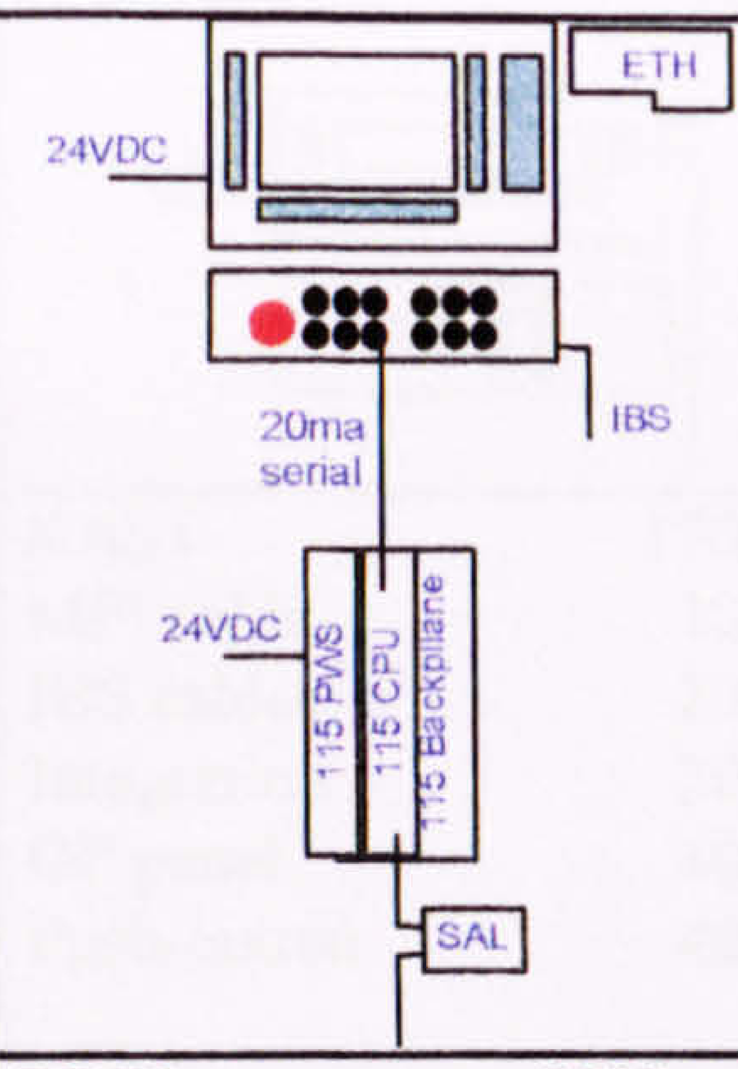
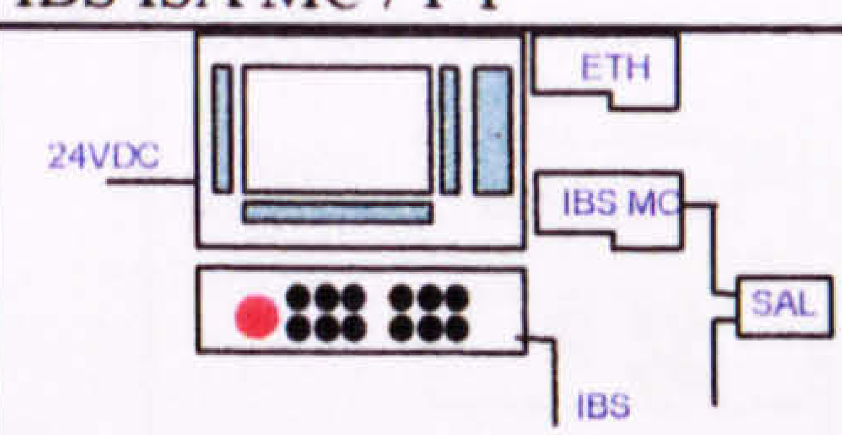
Figure C 2 Site 2 Test Rig Configuration.



C1.9 Typical configuration cost evaluation (Site 1 / Site 2)

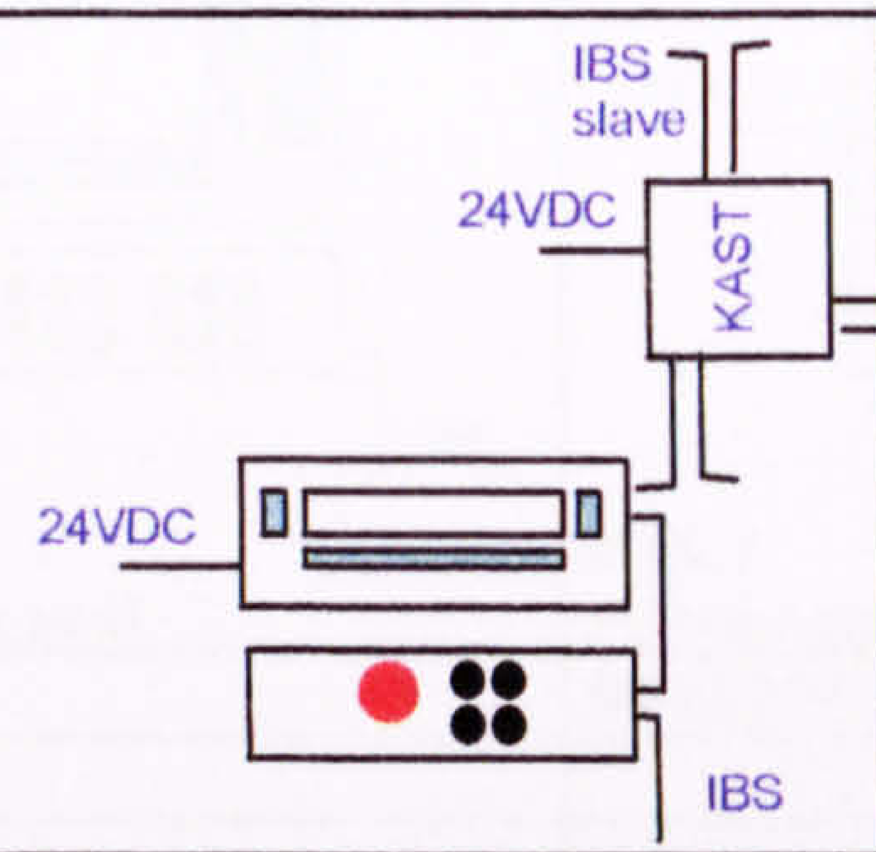
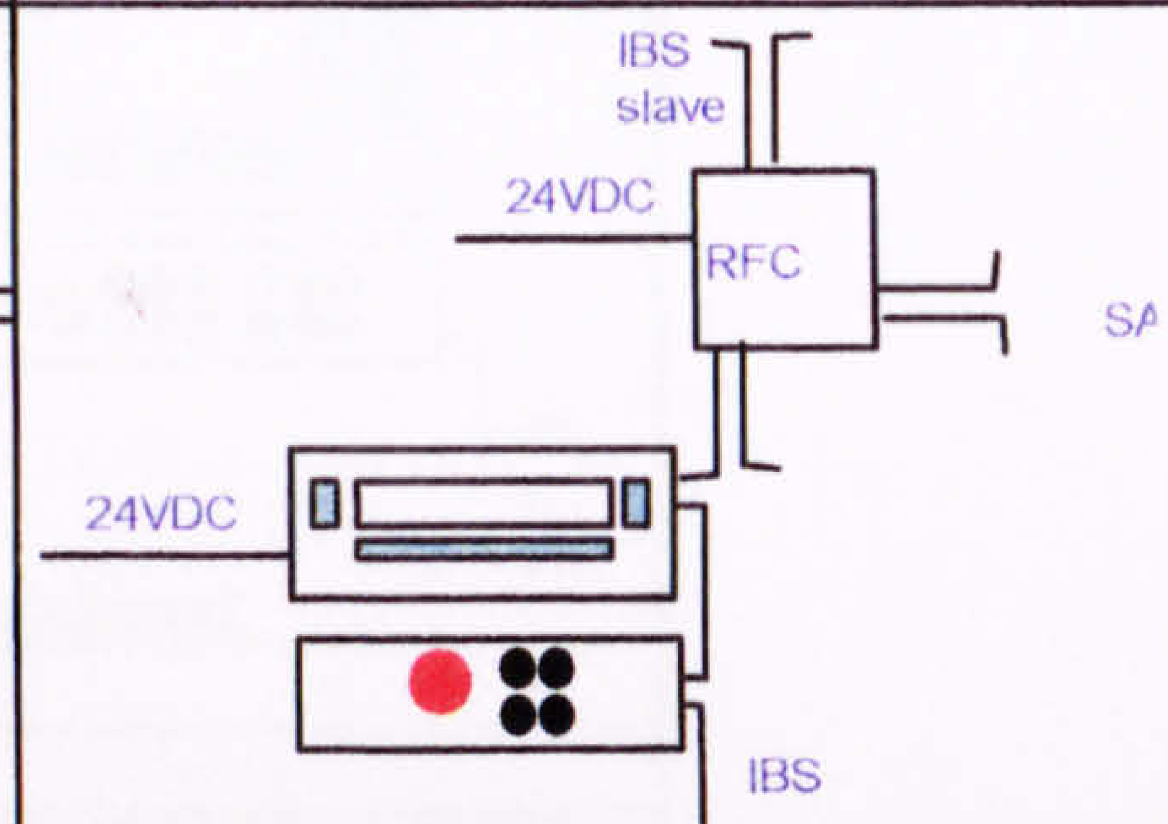
Assumptions

- motion is Indramat.
- I/Os based on IB-S modules or SAL (Interbus-Loop)
- Assume I/O identical cost on both systems.
- PC based MMI

MMI	Control	Site 1 Siemens		Site 2 NGC	
OP PC		S5-115		IBS ISA MC / I-T	
	Seq				
OEM Net Price		BPC2	5500	BPC2	5500
		ISA slots	500	ISA slots	500
		Ethernet	200	Ethernet	200
		MMI Panel	400	MMI Panel	400
		CPU 941	793	IBS MC	1190
		PS 951	651	Integration	200
		Backplane	238	SAL	500
		S5 IBS-M	2000		
		Serial cable	100		
		Integration	400		
		PLC panel	400		
		SAL	500		
			DM 11682		**DM 8490**
		CPU943	**DM 13505**	IBS MC 486	**DM 9510**

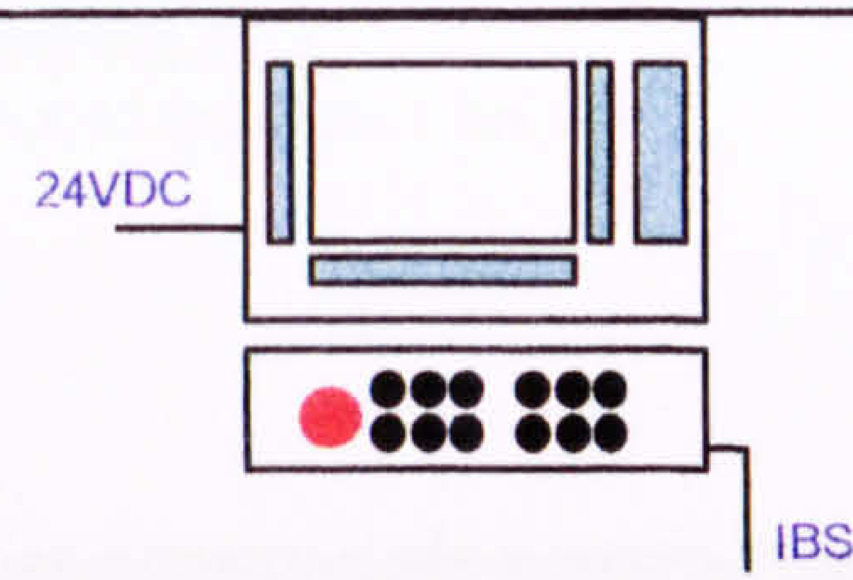
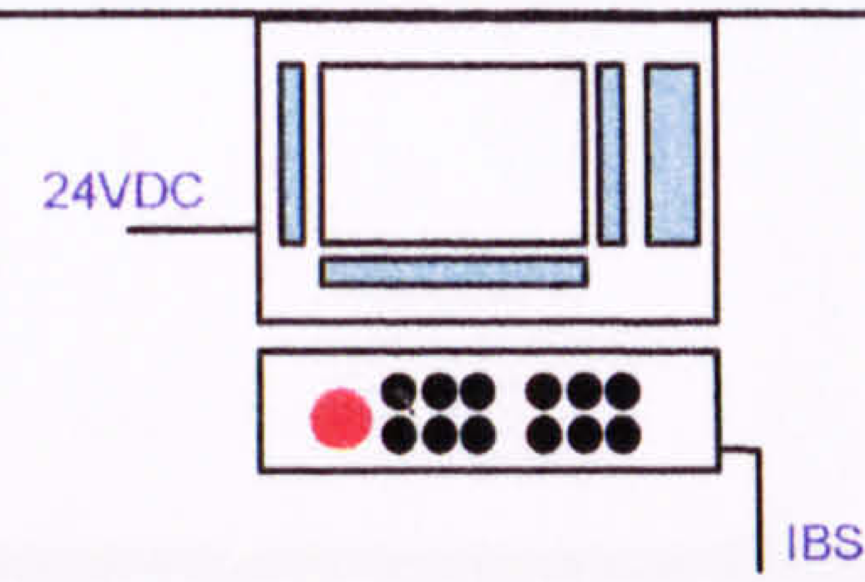
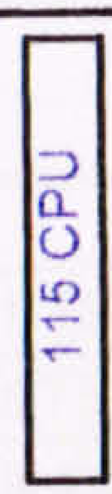
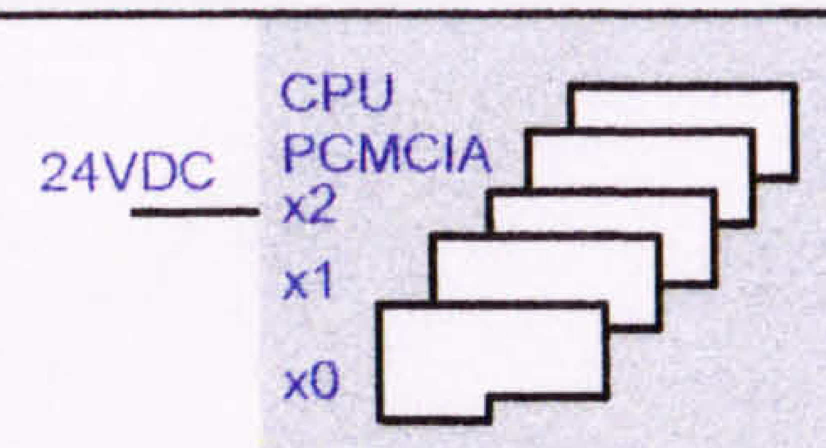
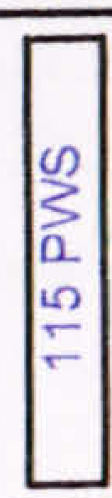
Assumptions

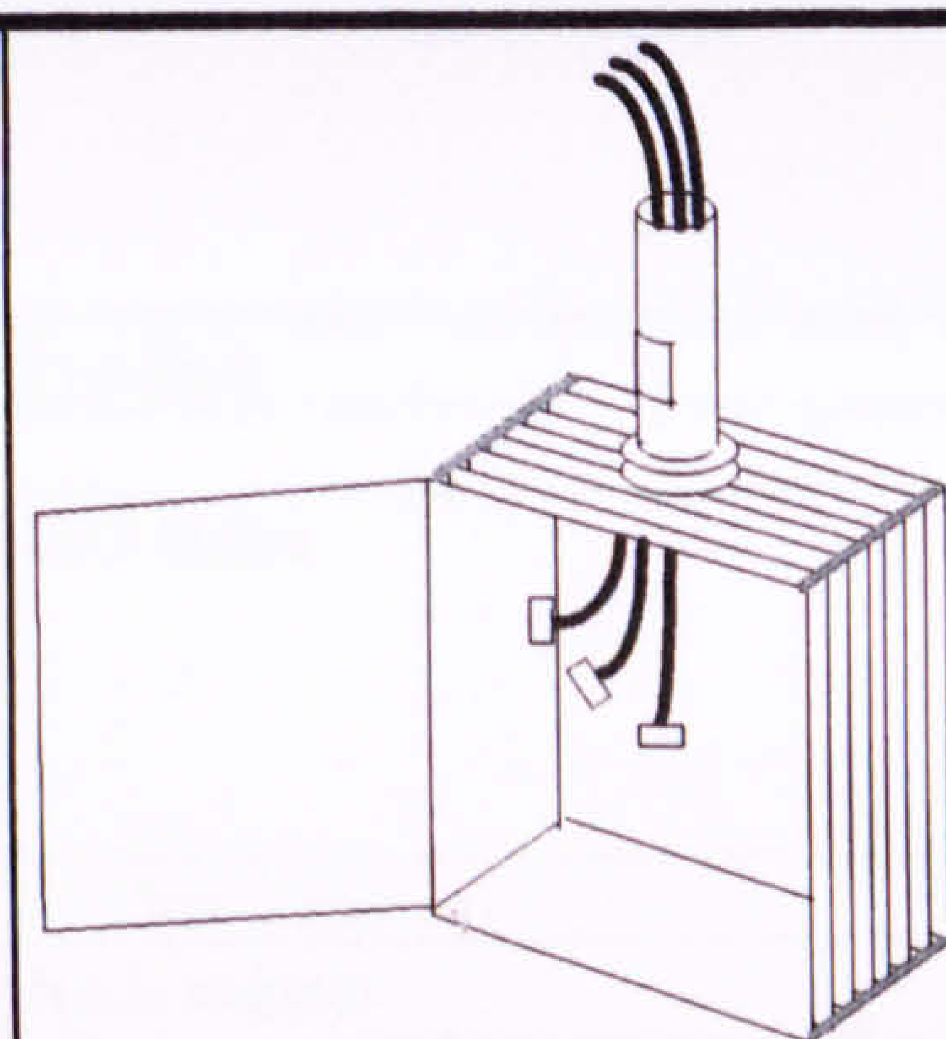
- Data-liner based MMI

MMI	Control	Site 1 Siemens		Site 2 - NGC	
Data liner		IBS ISA MC / I-T			
					
OEM **Net Price**		KAST MPI cable IBS cables Integration OP panel Push-button	1700 100 200 200 400 400	RFC MPI cable IBS cables Integration OP panel Push-button	2100 100 200 200 400 400
			DM 3000		**DM 3400**

Assumptions

- PC based MMI

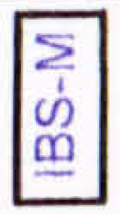
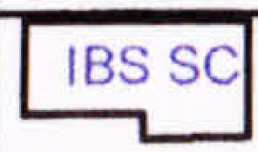
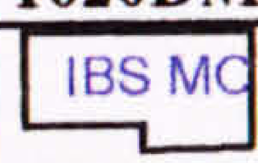
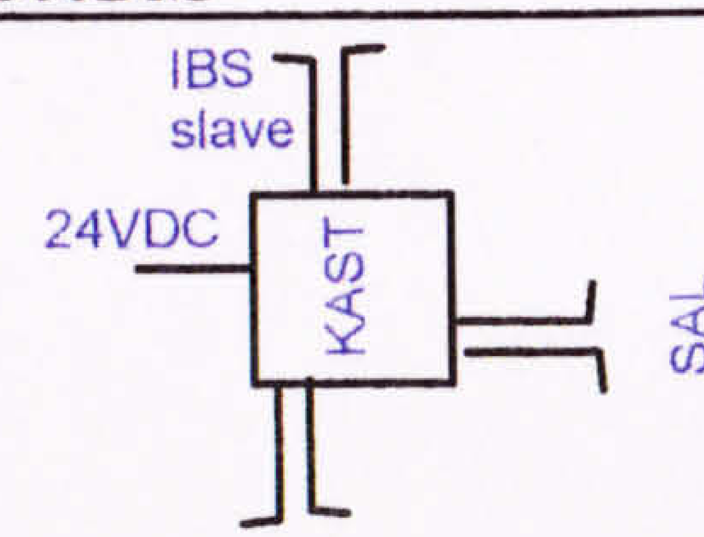
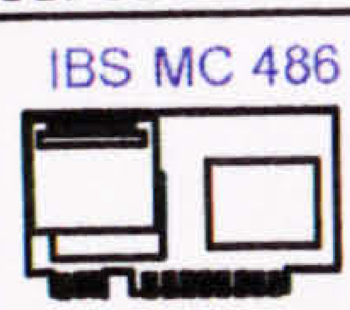
MMI		
	 **BPC2** PC based operator panel	 **BPC3** PC based operator panel
Net Price	**5500DM**	**5000DM**
Control		
S5-115	 **CPU 941/943** S5 115 CPUs	 **EMC-ISA-5** Embedded controller
Net Price	**793 DM (941)** **2516DM (943)**	**500 DM**
	 **PS951** PLC S5 PWS DC24V; 5V, 3A	 **ISA Ethernet card** Ethernet card
Net Price	**651DM**	**200DM**

	 **CR700-0LA** PLC S5 Backplane, 4 free slots	
		VIP6000 Rittal housing BPC housing
Net Price	**238DM**	**400DM**

I/Os IP67	
	8 DI; 24VDC
Net Price	**671DM**
	8 DO; 24VDC, 0,5A
Net Price	**756DM**
	8 DO; 24VDC, 2A
Net Price	**807DM**
	16 DI; 24VDC, 16DO 2A
Net Price	**1610DM**

Note: For IP67 I/Os add 20% for connectors

C1.10 Phoenix

Product	Phoenix	Product	
Control			
IBS Master	 **S7 300 IBS Master** S7-300 IBS master module	**IBS Slave**	 **IBS ISA RCI /I-T** ISAIBS Slave
Net Price	**1020DM**	**Net Price**	**500DM**
	 **IBS ISA SC /I-T** ISA IBS master module	**SAL master**	 **SAL Master** SAL Master
Net Price	**1020DM**	**Net Price**	**500DM**
IBS Master and PLC	 **IBS ISA MC /I-T** ISAIBS Master and PLC CPU	**IBS Master and PLC**	 **KAST** IBS Master, IBS Slave, SAL PLC CPU
Net Price	**1190DM**	**Net Price**	**3000DM**
	 **IBS ISA MC /I-T** ISA IBS Master PLC CPU 486 base		
Net Price	**2210DM**	**Net Price**	

C1.11 Option 1 - Siemens S5. Line Based Staff Training Requirements

Course Type	Days Req.	Pre-requisites	Trainer Difficulty Assessment
PLC Background	5 Days	Non Electrical Background	**
Drives Background	1 Day	Non Electrical Background	**
Siemens S5 PLC	5 Days	Electrical +	***
Interbus S / Phoenix	3 Days	Electrical +	***
Siemens Moby I	2 Days	Electrical +	***
Axis Controller Cards	2 Days	Electrical +	****
Nutrunner Technology	2 Days	All	**
Krause Structured Software	5 Days	Electrical +	***
Indramat Drives	2 Days	Electrical +	**
PC / PLC Comms.	1 day	Electrical +	***
Kadess	5 Days	Electrical + 1	**
Operator Course	2 Days	All	*
	35 Days		**30**

Specialist Back Up Staff

Siemens S5 PLC	5 Days	If required
Interbus S / Phoenix	3 Days	If required
Siemens Moby I	2 Days	If required
Axis Controller Cards	2 Days	If required
Nutrunner technology	2 days	All
Krause Structured Software	5 Days	All
Indramat Drives	2 Days	If required
PC / PLC Comms.	1 day	If required
Kadess	5 Days	All
	27 Days	

C1.12 Option 3 - Embedded Controller. Line Based Staff Training Requirements

Course Type	Days Req.	Pre-requisites	Trainer Difficulty Assessment
Embedded Controller Background.	2 Days	All	**
Drives Background	1 Day	All	**
Interbus S / Phoenix	1 Days	All	**
Data Tagging System.	1 Days	All	**
Nutrunner Technology	2 Days	All	**
Krause Structured Software	5 Days	Electrical +	***
Indramat Drives	2 Days	Electrical +	**
Kadess	5 Days	Electrical +	**
Operator Course	2 Days	All	*
	21 Days		**18**

Specialist Back Up Staff

Embedded Controller	10 Days	All
Nutrunner Technology	2 Days	All
Krause Structured Software	5 Days	All
Indramat Drives	2 Days	If Required +
Kadess	5 Days	All
	24 Days	

APPENDIX D

CONFERENCE PAPERS

ICP Conference, September 1996, Paris.

Next Generation Control Systems in the Automotive Industry

Leslie J. Lee
School of Manufacturing Engineering
Loughborough University of Technology.

Abstract

This paper presents an argument that the proprietary Programmable Logic Controller (PLC) used by the Automotive Industry for the last twenty years, is now in terminal decline.

Some of the challenges facing the Automotive Industry and its PLC suppliers are considered, and next generation machine controller requirements are reviewed.

Sequential programming techniques currently used in PLC's are examined and contrasted with fully distributed, event driven structures. A generic model of an event driven system is presented, along with a description of the physical and logical layers of the model. Finally the potential advantages and concerns of this approach are considered.

Introduction.

Extraordinary change is taking place in industry. The global market place has increased the automotive manufacturing industry's demands for systems that match their particular needs. The rapid pace of technology is continuing to shorten product life cycles, while product development, launch and maintenance cost are escalating.

Initial findings from research in progress at Loughborough University suggest that current manufacturing control systems are not fulfilling the Automotive Industries requirements. Shorter product life cycles, rapid change-over, systems unsuited for multi-skilled operation and global availability are all problems highlighted by end users. The traditional Programmable Logic Controller (PLC) suppliers also face problems related to decreased revenue for a given number of systems, combined with increased competition and support requirements.

The aim of this paper is to present an argument that the proprietary PLC used by the Automotive Industry for the last twenty years, is now in terminal decline.

Some of the challenges facing the Automotive Industry and its PLC suppliers are examined, and next generation machine controller requirements are reviewed.

Sequential programming techniques currently used in PLC's are discussed and contrasted with fully distributed event driven structures. A generic model of an event driven system is presented, along with a description of the physical and logical layers of the model. Finally the potential advantages and concerns of this approach are considered.

Background.

The publication of a white paper by North America's three largest Automotive producers in December 1994, may prove to be a significant turning point for manufacturing control systems. The paper outlined the requirements for open modular control systems (OMAC 1994). The Open Modular Architecture Controller (OMAC) report highlights numerous problems with proprietary controllers that, while presented from an automotive viewpoint, are true of many other industries.

General Motors dismay with current PLC systems and their programming languages has been graphically demonstrated on their recent Powertrain projects in North America. In excess of two hundred 'open' P.C. based control systems are in use. The programming language used is a flow diagramming technique called FloPro®; developed by a small company called Universal Automation. (Now owned by Nematron).

The programmable logic controller was initially conceived by engineers from the General Motors Corporation in 1968. (Warnock 1988) The *initial specification required that the controller* must be:

- Easily programmed and reprogrammed, preferably in plant, to alter its sequence of operations.
- Easily maintained and repaired - preferably using plug-in modules.
- More reliable in a plant environment,
- Smaller than its relay equivalent.
- Cost competitive, with solid-state and relay panels then in use.

As PLC technology became available in the early 1970's the automotive industry was one of the first major industrial sectors to utilise the systems.

The original specification for PLC systems and subsequent end user pressure led to the PLC being used as a relay panel replacement system for many years. The development of ladder logic as the main stream programming language reflected end user requirements for systems that mimicked the operation of the relay panel they were replacing. The suite of panels that once housed the relays was replaced with a centralised PLC system. Incredibly some quarter of a century later, ladder logic is still the dominant programming language in the Automotive Industry.

In 1990 a team of engineers at Ford Motor Company responded to an engineering led investment efficiency initiative with a distributed PLC solution (Figure 1). The machines being controlled consisted of a number of machining heads positioned on both sides of a part transfer system. (Figure 1) The centralised PLC was replaced with a small 'mini' PLC controlling discrete sections of the machine tool. Each section was linked via a real time serial network back to a co-ordinating controller.

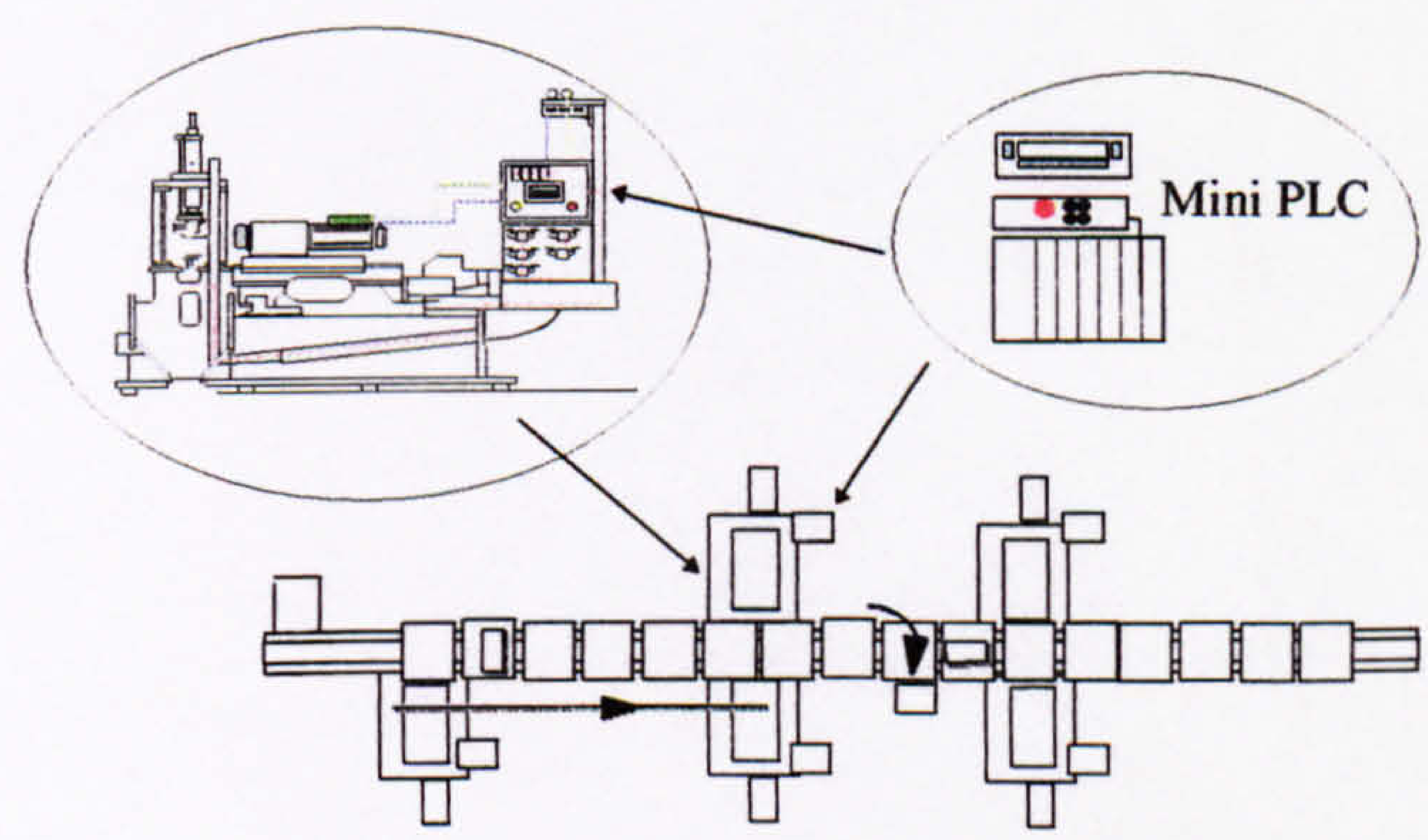


Figure 1 PLC Architecture.

Some savings were made in PLC hardware cost; however the majority of the investment reduction came from the modularization of hardware, software and documentation. The distribution of control to this level allowed the development of five basic designs of machining head and a standardised transfer mechanism. Engineers were able to commission individual heads before the machine was complete reducing lead time. Various combinations of standard machining heads were then grouped together and connected back to the co-ordinating controller. The standardised software significantly reduced the amount of software engineering required. The combination of these factors led to greater reliability as well as the desired investment reduction.

Splitting the control program into a number of discrete sequences simplified the control programs making them easier to maintain on the shop floor. The processing load (scan time) on an individual controller was reduced from typically 60 milli-seconds with a centralised controller architecture, to 5 milli-seconds on each of the distributed PLC's. The system scan time including the serial communication was less than 20 milli-seconds. The reduction in scan time simplified mechanical and electrical design.

Following the successful implementation of this system on a major engine programme it has now become widely accepted within the Automotive Industry as the benchmark for this type of machine architecture.

Manufacturing Challenges

Before next generation control system requirements are discussed, it is important to gain an overall appreciation of the whole environment in which the problem must be addressed.

The decline in PLC order value is dramatically illustrated by comparing two recent Automotive Powertrain projects (Ford 1994). Five years separate the two programmes; during which time the PLC supplier's order value fell by 80%. The reductions can be attributed to more powerful products at lower cost, the increasing use of third party I/O bus systems and better use being made of products due to the introduction of Simultaneous Engineering Teams.

During this same period when order value has been falling dramatically, end users have been demanding increased support from the control suppliers. The manufacturing plants expect structured software programs, spare parts placed on site at the control suppliers cost, five year warranties and instant on site assistance during the start-up period. These support requirements have been financed from the dwindling order value outlined above.

It can be shown that approximately 50% of the control supplier's profit will be generated from input and output cards, 25% from processor cards and racks and 25% from operator screens and display systems. An explosion in the use of bus connected input / output modules from a third party, and hence the loss of the PLC manufacturers biggest profit generator, may be about to turn a difficult position for the control suppliers into an impossible one. The lack of high technology devices to develop and support, often allows third party suppliers to operate with lower overheads so making their products very cost effective.

The increasing complexity of machine tools and introduction of multi-skilled operation in the end user's factory, has made both the end user and machine tool builder increasingly reluctant to change from their own build standards. The machine tool builders (OEM's) wish to impose their standards to keep engineering / training costs down and reliability high. The manufacturing plants need to integrate machines from a number of manufacturers into a production system. They want common standards on all machine tools for much the same reasons as the OEM's. Unfortunately for the end user, if he is integrating ten different suppliers machine tools, he is likely to have ten different, incompatible control systems.

Because of the proprietary nature of the existing PLC systems, the end user is left with two choices; to impose his own standards and run the risk of timing and cost penalties, or purchase machine tool builder standard machines and pay the price in operating efficiency. A compromise is normally sought between investment and timing constraints as well as plant preferences and regional support capabilities. *It is emerging that due to changing working practices the large Automotive end users cannot tolerate this compromise for much longer.*

Other challenges facing the automotive industry are shorter product life cycles, flexibility at high volume and quick changeover. Global competition has increased pressure on investment and operating cost. Machines are still built to last ten to fifteen years. If Powertrain product lifecycle is only five to seven years, the cost to reconfigure machines must be taken into account when facilities are originally designed.

The challenges outlined are summarised as follows:

- If support requirements are to be contained within the cost of the PLC, the decline in total order value must be addressed. Alternatively products which require far less support are required.

- The skills required to maintain machine tool control systems must match those available in the manufacturing plants.

- Control systems must be 'open' and available on a global basis to allow the OEM's and

Project Departments to accommodate regional preferences without the need for complete re-engineering.

- Scaleable systems, designed to be easily modified in mid-life to accommodate shorter product life cycle are required.

Next Generation System Requirements

The challenges outlined do not translate directly into a number of isolated features that can then be designed into a new product.

The reduction in order value for high technology suppliers and increasing support requirements can be addressed as a single problem. End users could pay for support from the PLC supplier separately. A better means of resolving this issue may be to commercially link the use of PLC systems with products that are already a commodity and require little support. For example the PLC contract could be linked to standard products (relays, push buttons, etc.), sensors or drive systems. A contract linked in this way will allow support requirements to be carried across a larger supply base and hence higher order value. Of course fragmenting the order value as part of the drive for 'open' solutions will only serve to make the situation worse.

Next generation control systems must be based upon products which are designed independently, and can then be integrated with other products from other vendors without the need to develop special programs, hardware or tools. The system must be fully documented, freely available, managed and promoted by a multi-national independent body. Independent certification of conformity will be required. (Harrison 1995).

Such a system must break the link between hardware and software development. It must allow machine tool builders to re-use much of their engineering and yet accommodate many of the end users' standards. Machine tool builders must be able to efficiently move from a job in Germany using company A's equipment, to another in North America using company B. Globalisation by the big Automotive users not only makes this an OEM requirement it is now an end user requirement.

The big PLC manufacturers are in a difficult position as there are risks involved in the change to open systems. However, with more and more systems coming on to the market the genie is already out of the bottle (ARC 1996). The question must be not if, but when, the change must be made. The leading mainframe computer and minicomputer suppliers ignored, resisted or minimised the PC revolution, and the effects on those suppliers are still being felt today. Some of the once-major companies are gone, several are struggling for survival. A few have now changed their strategy and begun to support open systems, albeit late in the game and at a very high cost (Lonmark 1994). From an end user perspective it seems that some of the PLC suppliers are turning their back on change or worse still try to resist it?

Shorter product life cycles demand agile production facilities. Machines designed for use on high volume lines should not be confused with flexible machining centres found on low volume facilities. High volume machines need to be quick and simple, which often leads to custom design, making them difficult and expensive to reconfigure. If the products produced by the machine tools are to have a shorter life cycle, either the machines need to be half their present cost, or they need to be reconfigured quickly and cost effectively in mid-life. This requirement demands a control system that is scaleable and able to accommodate changes in complexity a number of years after the original control system was supplied.

The system must be designed to be operated and maintained by multi-skilled personnel and programmed / reprogrammed by the engineer who is designing the process. This will require the development of 'Process Development Languages'; the declared aim of which, must be to eliminate the software engineer from the programming of machine tools. (Figure 2). It is unlikely that the current IEC1131/3 languages will be able to fulfil this requirement.

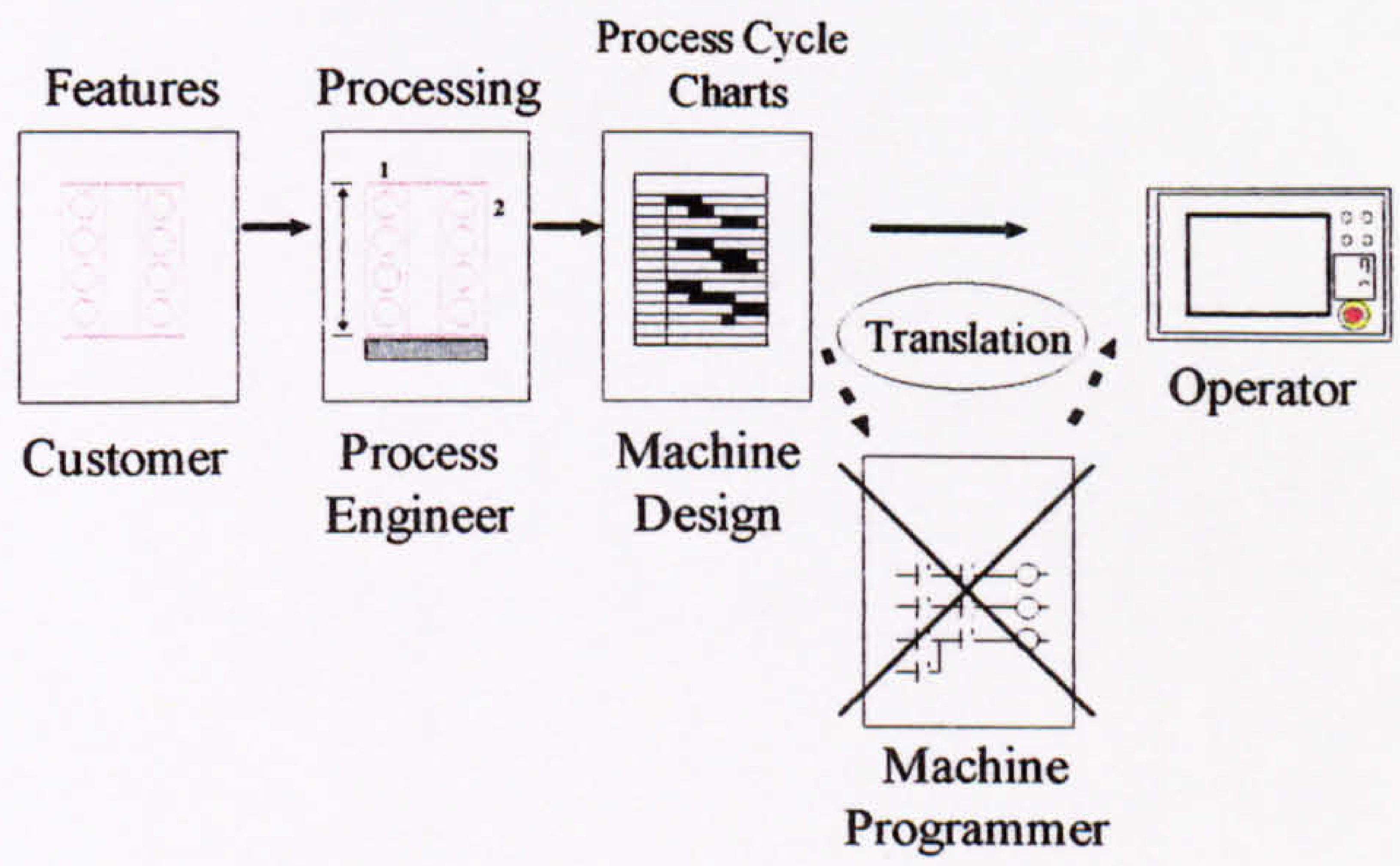


Figure 2 Process Development Languages.(Lomax 1994)

It is not clear if the major control suppliers are ever going to allow complete portability of applications programmed using the existing IEC1131 languages; therefore the standardisation and portability of the new process development languages will present a major challenge.

Control System Evolution

The evolution of the machine control architecture has followed a steady course for a number of years. The original PLC systems utilised a central processing architecture with centralised input and output racks. This was a natural first step as it directly reproduced the structure found in a relay system. This was followed by centralised processing with remote input and output modules fitted into sealed cabinets around the machine. In the early 90's multi-sequence machines went to distributed processing and distributed input and output modules. This architecture requires the use of 'mini' PLC's located in small panels adjacent to the machining station. Recently the Input and Output modules have started to move out of the station panel to be replaced by field mounted IP67[1] blocks.

Some would say that Personal Computer (PC) based technology will become next generation control system for machine tools. This development will certainly promote further, 'open' control systems; however the PC controller will simply be used to replace the existing proprietary central processing unit (CPU.) *It can therefore be considered an advance in hardware and not an advance in machine control architecture.*

Using the established path of the past twenty five years it is clear that where the input and output blocks go, the intelligence soon follows. Therefore the next logical step is to embed the control of a device and its interaction with other devices into IP67 blocks.

Fully Distributed Event Driven Structures.

Introduction

In conjunction with Loughborough University of Technology, Ford Motor Company is in the process of developing a fully distributed event driven system for use on machine tools. The aim is to produce a system that will eliminate many of the problems evident in centralised and partially distributed systems. Whilst the research is ongoing sufficient work has been completed to establish a generic model.

The concept of a fully distributed machine control system is to replace the distributed PLC with a number of controllers, physically located at the point of control (Harrison 1996). To implement this architecture machine elements are broken down until a small piece of generic code can be applied to the function. Each controller is known as a node.

Before a new model could be developed; the generic features found in existing systems were reviewed to establish machine control 'requirements' and 'attractive features'. The requirements are not fixed and as with other

[1] An IP67 device is sealed against the ingress of dust and water and so can be mounted directly on the machine.

products; over time the 'attractive features' become 'requirements' expected of the system.

Sequential Control of Machine Tools.

An application program consists of a number of processes, some are independent whilst many are inter-related. The vast majority utilise some form of sequence controller to schedule events to take place in a logical order. To optimise machine cycle time it is often the case that a number of sequences will operate concurrently within a single PLC controller.

Multi-sequence control programs are often complex and require the prioritisation of operator and fault messages. Each sequence will have a fixed overhead associated with its existence, this increases the memory requirement and hence scan time of the PLC. One of the drivers for partial distribution of control was to reduce the number of sequences within a single PLC.

A number of structured programming techniques are in wide spread use in the Automotive Industry. Analysis of the PLC code produced from these techniques highlights a consistent set of control requirements. The test of a good program structure is not how well it handles the relatively simple task of controlling the machine in automatic cycle; but how it handles machine faults, operator information, error recovery and manual operation.

Sequential Programming 'Requirements'.

Sequential Control: The program must be able to control a fully automatic sequence of operations.

Sequence Check: This term is used to describe an interlock condition that must be satisfied before the next function can occur. This must not be flagged as a fault condition unless the maximum step time is exceeded.

Interlock Fault. This type of interlock condition will stop a machine tool immediately. The code must recognise that an actuator has moved out of sequence. An example of this is a clamp switch deactivating during a cutting cycle. Some interlock conditions will be monitored during certain steps. Others will be monitored constantly, for example Hydraulics or Air. The code must be able to differentiate between a 'sequence check' and 'interlock fault.'

Manual Interlocking: The majority of machine tools will have a protected manual. Manual interlocks are often different to automatic interlocks and are designed to give as much freedom of movement as possible whilst ensuring that machine damage does not occur.

Sequential Programming 'Attractive Features'

Set-up Mode. This mode of operation is often called maintenance mode. It is used during the commissioning or maintenance of the machine and overrides all software interlocks in manual mode.

Initial Position Function. Some structured techniques allow the operator to return the machine to initial position using a single push-button. The manual interlocks are used to ensure that elements do not clash.

Diagnostics

Sequence and Error Message Display. Operator messages are displayed to indicate the position in the step sequence as well as sequence errors.

Manual Cross Interlock Check. If a manual push-button is pressed the system can display the interlock conditions that prevent that operation functioning (if any)

Operator Display Prioritisation: Often a single control program will have multiple independent sequences. A prioritisation algorithm must be developed to ensure that the most significant problem is displayed. It is normally not sufficient to give sequence one the highest priority. It could be that sequence one is 'waiting for a component' (sequence check) and sequence two has an interlock fault caused by an unauthorised actuator movement.

Physical / Logical Layer

The control elements of the development machine have been broken down until a small generic function can be identified. At this level the control function of a two position solenoid is the same as a reversing contactor; a relay has the same function as a single acting spring return valve, and so on. A small piece of generic code has been written for each of the device categories. Each node controls a single actuator and its associated input sensors. It is possible that a node may not have an actuator, or may not have sensors. Full distribution has occurred when the node is able to utilise one of the standard pieces of code. A number of nodes are then be formed into a function group as shown in Figure 3

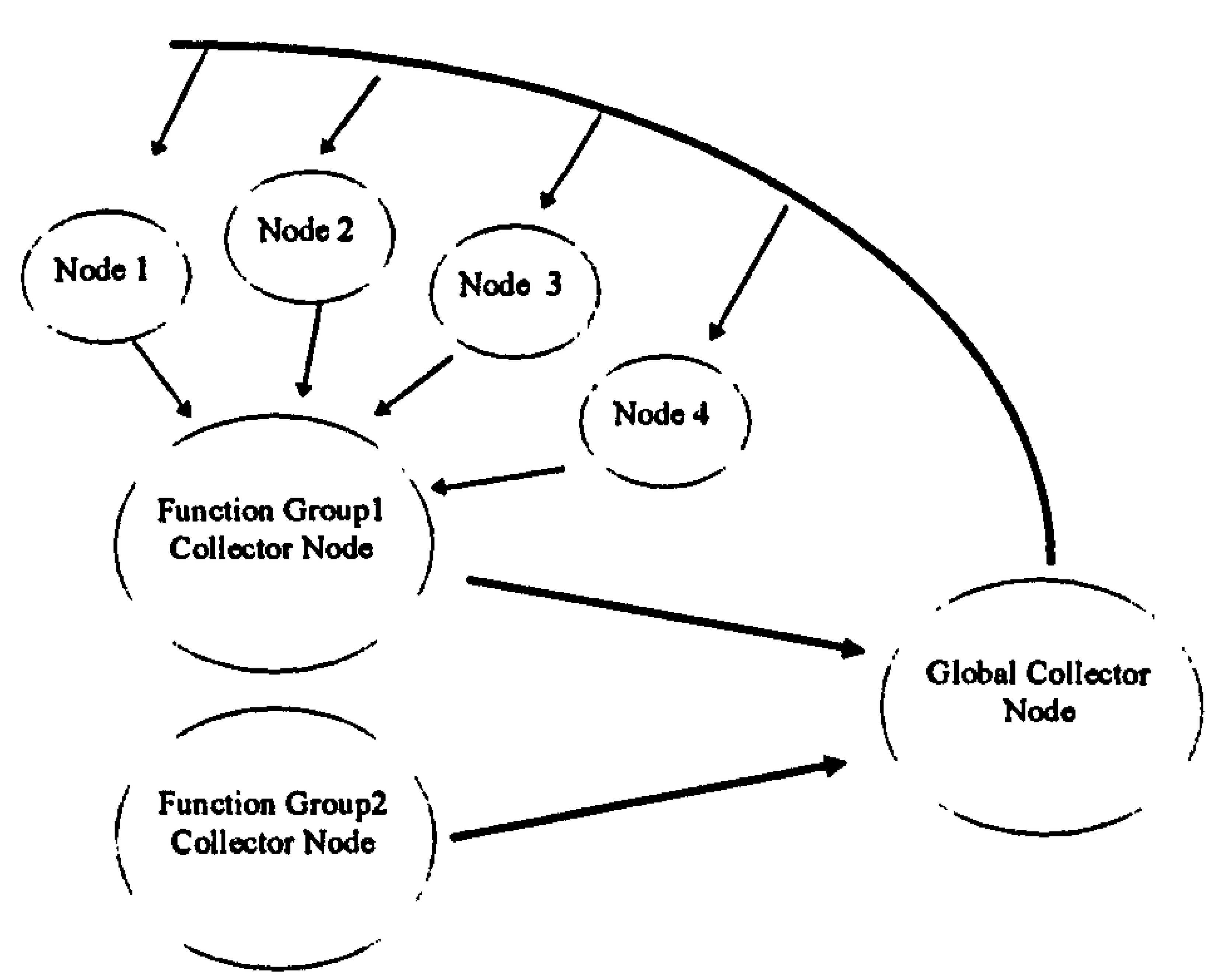


Figure 3 Node Architecture

Embedding tried and tested software into the node eliminates the need to programme equipment. The system will instead, require the elements of a machine to be identified and then linked for automatic and manual operation. The translation process that occurs when the Controls Engineer converts the mechanical timing charts into machine logic is no longer required.

When the node has been initialised (All Nodes Enabled) every node in the system will attempt to go to its work position. The only inhibitor stopping this occurring is the automatic interlocks. Immediately the node reaches the work position it will attempt to return to the home position. Again the only inhibitor is the automatic interlocks. It should be noted that 'start cycle' is a node which issues an interlock in the same way as a physical device.

The event driven code eliminates the need for a step sequence and instead relies solely on the interlocks to constrain elements of the machine. Potentially this will produce control programs that self optimise to the most efficient cycle. If a fault occurs causing an element to slow down, (e.g. due to an oil leak in a cylinder) it is possible that the sequence of operations will change to take into this into account. Node scan time will be negligible due to the small amount of embedded code, network speed will be critical.

The input and output signals required by each node have been defined in figure 4.

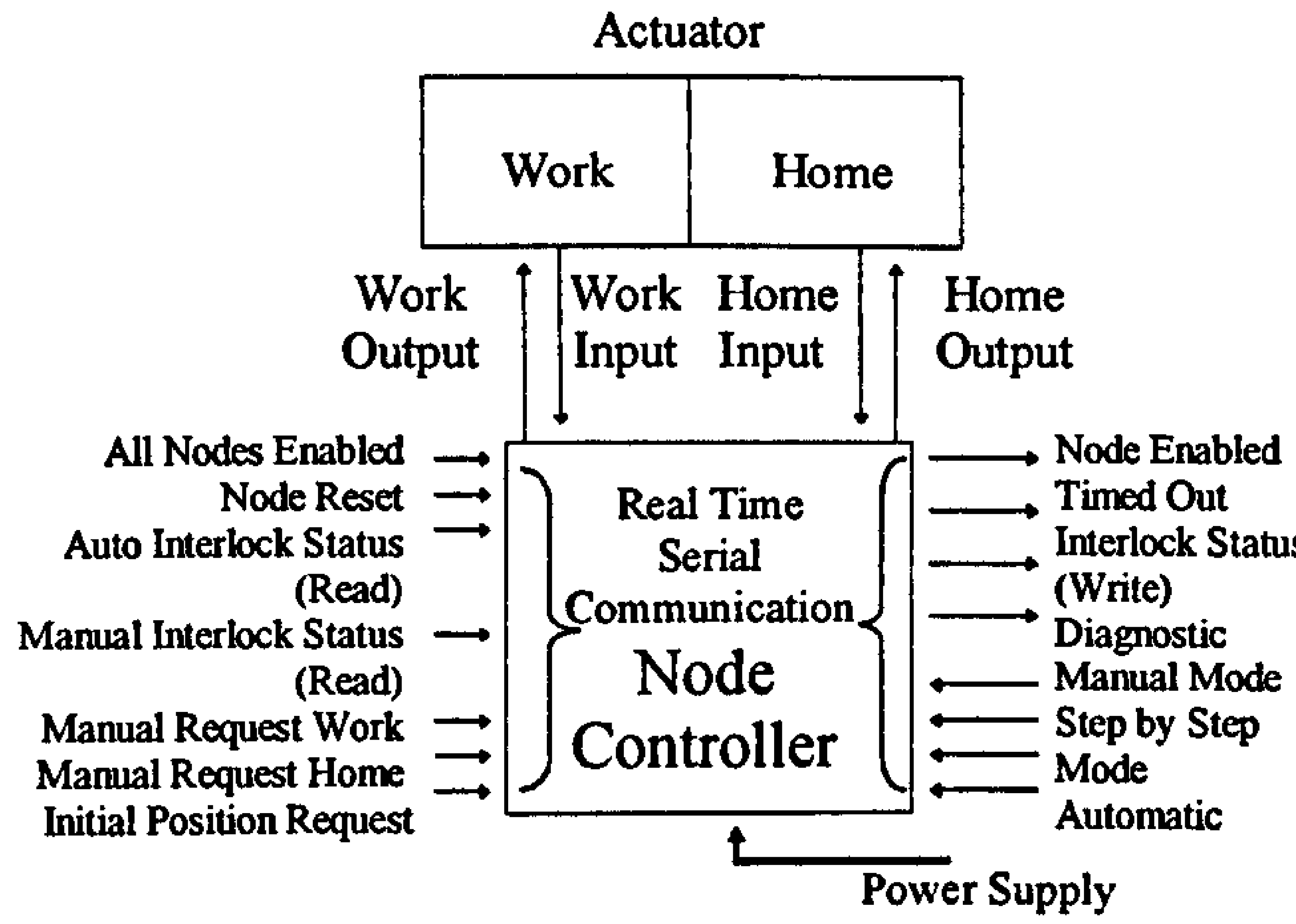


Figure 4 Logical Input and Output Signals.

Conclusions

In this paper a generalised methodology for the implementation of a fully distributed control strategy using event driven code has been outlined. Tests have demonstrated that machines can be returned to initial position using the methods shown. Future work will establish if full control can be transferred to this system.

Interoperability at a *'plug and play'* level will be a key requirement for future control systems. A part or product, regardless of manufacturer must be able to integrate into the system with the minimum of effort. Interoperability doesn't just happen. A comprehensive organisational structure and well defined standards will be required. It may be the case that this will be a natural extension to the work of the IEC1131 committee and the [2]PLCopen association.

The fully distributed approach outlined, even at this early stage in its development, has shown the potential to solve many of the end users concerns whilst providing a viable path to 'open' systems requiring very little support.

Whilst embedding the control into IP67 blocks is likely to be the first step, eventually the control will be embedded into the standard control products, (e.g. relays, contactors, motors, valves, etc.).

The system has the potential to improve machine reliability through the use of tried and tested code. As the technology continues to fall in price, it will be possible to build redundancy into the node allowing the manufacturing facility to continue production whilst a new part is obtained. The incorporation of the node into the valve, motor or other actuating device will simplify maintenance and support the use of multi-skilled labour to operate and maintain the production facility.

The aim of the 'fully distributed' initiative by Ford is not to make the life of the current programmer easier. It has as one of its central design goals, the elimination of the application programmer completely. •

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[2] PLCopen is a product independent association promoting the use of IEC1131. Their registered office in Europe is in Zaltbommel in the Netherlands.

APPENDIX E

ENGINE ASSEMBLY SYSTEM – TIERS OF ARCHITECTURAL COMPLEX

Table Error! No text of specified style in document.**-1 Architectural Complex Tier 1**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology	Conformance Criteria
Scope: ***Control a wide variety of machine tools and equipment used for automotive manufacture in a 'lean' manufacturing environment..*** **Purpose:** 1. Closely align control architecture with manufacturing strategy. (e.g. multi-skilled, team based operation) 2. Support (if necessary) structural organisational change. 3. Focus on life cycle cost.	*Operational*: 1. Globalisation of manufacturing technology and operations. 2. Fragmentation of customer requirements. 3. Increasingly complex end products. 4. Rapid product and process technology change. 5. Environmentally conscious manufacturing. 6. Global over capacity. 7. Productivity measured against global competition. 8. Manufacturing used as a competitive weapon. 9. Increasingly onerous statutory legislation *Information:* 1. Compliance with statutory legislation.	None specified at this tier.	1. Architectural units identified in lower tiers are partitioned into manageable units. 2. Architectural units are as functionally independent as possible. 3. Architectural units have high degree of functional relevance of elements within a unit. 4. Architectural units are independent of global variation (voltage, frequency, local support). 5. Units conform with statutory legislation. *Design methodology*: STS analysis	1. Has each unit has been life cycle assessed? 2. Does each unit support operational strategy? 3. Are the units in lower tiers decomposed into sub tasks? 4. All units identified in lower tiers conform with statutory legislation?

Table Error! No text of specified style in document.**-2 Architectural Complex Tier 2**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology	Conformance Criteria
Scope: ***Control of a wide variety of machine tools, and equipment used for engine manufacture.*** **Purpose:** 1. Provide low life cycle cost control systems 2. Facilitate scalability 3. Sponsor system agility. 4. Allow architectural units to designed independently and integrated with other products from other vendors without the need to develop special programs, hardware and application software. 5. Where possible utilise certified 'open' systems managed and promoted by a multi-national independent body 6. Eliminate the link between hardware and application software development 7. Facilitate the programming and re-programming of machines by mechanical or process engineers. Note: Decisions made in this tier must be consistent with those made at higher ones.	*Functional*: 1. High level tasks are decomposable into sub-tasks 2. Overwhelming majority of processes are sequential. 3. Deterministic performance. 4. Human safety not within scope of control system. (legislation dictates hard wired) 5. High system integrity required, (financial losses accrued quickly) *Operational*: 1. Multi-skilled operation and maintenance 2. Team based operation 3. Product and process changes carried out by 'Process' Engineer.	*Atomic / Architectural Units:* 1. All Atomic / Architectural Units identified in lower Tiers. 2. Specialised hardware units (welding, machining etc.) 3. Specialised software units.	1. Where possible utilise certified 'open' systems managed and promoted by a multi-national independent body. 2. Where possible utilise standard 'off the shelf' components. 3. Global Independence: Architectural complex to use 24v DC as main and external supply. *Design methodology*: STS analysis	1. Architectural units are independent of global variation (voltage, frequency, local support)? 2. Architectural Complex designed to accommodate unforeseen functions? 3. Where possible 'open system' architecture has been used?

Table Error! No text of specified style in document.**-3 Architectural Complex Tier 3**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology	Conformance Criteria
<u>**Zone Controller Tier.**</u> **Scope:** ***Control of Zones of machines and conveyor within a specified area. Master Controller for the co-ordination of several peer/lower tier controllers.*** **Purpose:** 1. Present, measure, prepare, and assemble engine component parts. Note: decisions made in this tier must be consistent with those made at higher ones	*Functional*: 1. Deterministic logic controller performance < 10 ms. 2. R.F. tagging of Engine carriers. 3. All discrete inputs and outputs transfer by serial communication. 4. Process development language 5. Power and scan failure detection required. 6. Remote and local monitoring of controller status. 7. Integrated fault and error checking of external devices.	*Atomic / Architectural Units:* 1. All Atomic and Architectural Units identified in lower Tiers.	*Design methodology*: Design Coupling Analysis, Design Cohesion Analysis.	

Table Error! No text of specified style in document.**-4 Architectural Complex Tier 4**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology	Conformance Criteria
<u>Complex Assembly M/C Tier</u> **Scope:** ***Complex assembly machines with multi-axis capability and/or greater than twelve actuators.*** **Purpose:** 1. provide controller hardware that meets machine performance requirements 2. provide controller application software that meets machine functionality requirements Note: decisions made in this tier must be consistent with those made at higher ones	*Functional*: 1. Requirement for integrated closed loop servo control. (max. 5 axis) 2. Process development language with integrated motion capability and consistent with lower levels. 3. High level operator interface with graphical and textual capability. 4. Low cost sensitivity	*Atomic Units:* 1. All Atomic Units identified in Tier 6. 2. High level operator interface unit. 3. Motion control unit. 4. Motion control, program development unit. *Architectural Units:* Non Atomic units: The following units may be integrated. 1. Central Logic processing Unit and High level Operator Interface Unit. 2. Motion control program development unit and logical control development unit	*Logical Interaction* : *Prescription* : *Design methodology*: Design Coupling Analysis Design Cohesion Analysis	1. Is Logical Control development software consistent with lower tiers? 2. Does the hardware and software meet the required system attributes of: • System flexibility • System agility • Operational Efficiency • Scalability • Availability • Accuracy / performance • Purchase cost See for attribute specification.

Table Error! No text of specified style in document.-5 **Architectural Complex Tier 5**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology	Conformance Criteria

<u>Elementary Assembly M/C Tier</u> **Scope:** ***Simple assembly machines and equipment with simple motion requirements and/or less than twelve actuators.*** **Purpose:** 1. provide controller hardware that meets machine performance requirements 2. provide controller software that meets machine functionality requirements Note: decisions made in this tier must be consistent with those made at higher ones	*Functional*: 1. No requirement for integrated closed loop servo control. 2. Process development language consistent with lower level 3. Low level operator interface with textual interface. 4. Medium cost sensitivity.	Atomic Units: 1. All Atomic Units identified in Tier 6. 2. Low level operator interface unit. *Architectural Units:* Non Atomic units: Due to cost constraints apparent at this tier level, the following units may be integrated. 1. Central Logic processing Unit and Sensor Actuator bus unit. 2. Power supply and System monitoring and security unit.	*Logical Interaction* : *Prescription* : *Design methodology*: Design Coupling Analysis Design Cohesion Analysis	1. Is Logical Control development software able to function on tier four hardware? 2. Is the hardware able to fulfil tier four functionality? 3. Does the hardware and software meet the required system attributes of: • System flexibility • System agility • Operational Efficiency • Scalability • Availability • Accuracy / performance • Purchase cost See for attribute specification.

Table Error! No text of specified style in document.**-6 Architectural Complex Tier 6**

Scope and Purpose	Domain Analysis	Atomic / Architectural Units	Architectural Specification and Design Methodology.	Conformance Criteria
Engine Transport Sys. Tier **Scope:** ***Engine Assembly conveyor systems.*** **Purpose:** 1. provide controller hardware that meets conveyor performance requirements. 2. provide controller software that meets conveyor functionality requirements Note: decisions made in this tier must be consistent with those made at higher ones	*Functional*: 1. Remote control of controller (e.g. central start/stop) 2. No / removable operator interface panel. 3. High cost sensitivity.	Atomic Units: 1. Central Logic Processing unit 2. Memory unit 3. Power supply unit. 4. Remote monitoring and control unit. 5. System monitoring and security unit. 6. Sensor actuator bus unit. 7. Logical control development unit. 8. Sensor Bus definition unit. *Architectural Units:* Non Atomic units: Due to cost constraints apparent at this tier level, the following units may be integrated. 1. Central Logic processing Unit and Sensor Actuator bus unit. 2. Power supply and System monitoring and security unit.	*Non Atomic units:* Due to cost constraints apparent at this tier level, the following units may be integrated. 1. Central Logic processing Unit and Sensor Actuator bus unit. 2. Power supply and System monitoring and security unit. *Logical Interaction* : *Prescription* : *Design methodology*: Design Coupling Analysis Design Cohesion Analysis	1. Is Logical Control development software able to function on tier five hardware? 2. Is the hardware able to fulfil tier five functionality? 3. Does the hardware and software meet the required system attributes of: • System flexibility • System agility • Operational Efficiency • Scalability • Availability • Accuracy / performance • Purchase cost

Figure Error! No text of specified style in document.**-1 Structured Scope Reduction**