Fractal architecture for 'leagile' networked enterprises

Aririguzo Julian Chika

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Preface

This thesis is submitted to the faculty of Arts, Computing, Engineering and Sciences of Sheffield Hallam University, Sheffield UK as part of the requirements for the award of the degree of Doctor of Philosophy.

It details the research carried out by me under the supervision of Professor Sameh Saad between March 2006 and August 2009.

No part of the work or material herein has been submitted for the award of any other degree or diploma in any university. To the best of my knowledge and believe, it contains no material previously published by any other body except where due acknowledgement has been made.

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Abstract

The manufacturing environment and markets in recent times are becoming increasingly dynamic, diverse and unpredictable, due mainly to fast evolution of products and technology, erratic customer behaviour and high consumerism and an increasingly shorter lead-time. The burden of the impact falls on organisational structures built on centralized, rigid manufacturing architecture, because they cannot cope or adapt to the highly uncertain or unpredictable nature of the market. Enterprises who wish to survive these challenges need to rethink their business and manufacturing models, and most importantly reinvent their tactical, operational and organizational formulas to leverage their strategic long term visions.

Newer manufacturing systems to curb the effects of this upheaval have to promote an entirely decentralised, flexible, distributed, configurable and adaptable architecture to ameliorate this condition. Many philosophies are proposed and studied towards planning, monitoring, and controlling the 21st century manufacturing system. These include - Bionic manufacturing system (BMS), Holonic manufacturing system (HMS), Fractal manufacturing system (FrMS), Responsive manufacturing etc.

This research program focuses on the FrMS, which has vast conceptual advantageous features among these new philosophies, but its implementation has proved very difficult. FrMS is based on autonomous, cooperating, self-similar agent called fractal that has the capability of perceiving, adapting and evolving with respect to its partners and environment. The fractal manufacturing configuration uses self regulating, organisational work groups, each with identical goals and within its own area of competence to build up an integrated, holistic network system of companies. This network yields constant improvement as well as continuous checks and balances through self-organising control loops. The study investigates and identifies the nature, characteristic features and feasibility of this system in comparison to traditional approaches with a detailed view to maximising the logistical attribute of lean manufacturing system and building a framework for 'leagile' (an integration of lean and agile solutions) networked capabilities. It explores and establishes the structural characteristic potentials of Fractal Manufacturing Partnership (FMP), a hands-on collaboration between enterprises and their key suppliers, where the latter become assemblers of their components while co-owning the enterprise's facility, to create and achieve high level of responsiveness. It is hoped that this architecture will drive and harness the evolution from a vertically integrated company, to a network of integrated, leaner core competencies needed to tackle and weather the storm of the 21st century manufacturing system.

Research papers based on this research

Saad, S.M and Aririguzo, J.C., "Fractal manufacturing partnership - a revolutionized manufacturing approach". *Proceedings of the 18th international conference on Flexible Automation and Intelligent Manufacturing*, FAIM2008, Skovde Sweden, 30th-2nd July 2008.

Saad, S.M. and Aririguzo, J.C., "Strategic integration of lean and agile paradigms in supply chain". *Proceedings of the 4th international conference on responsive manufacturing*, ICRM2007, Nottingham UK. 17th - 19th September, 2007.

Saad, S.M. and Aririguzo, J.C., "The emerging manufacturing systems - A comparative study". *Proceedings of the 5th international conference on manufacturing research, ICMR2007 incorporating the 23rd national conference on manufacturing research.* 11th - 13th September, 2007. Pp.307-312

Saad, S.M. and Aririguzo, J.C., " Simulating the integration of Original Equipment Manufacturer and suppliers in Fractal environment". *Proceeding of the international workshop on modelling and applied simulation* (MAS 2009), Tenerife - Canary Islands, 23-25 September, 2009.

Saad, S.M. and Aririguzo, J.C. "An Analytic Hierarchy Process approach to supplier selection issues of fractal manufacturing partnership".

Saad, S.M. and Aririguzo, J.C. "A Genetic Algorithm approach to modelling the fractal manufacturing layout".

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Chapter One

1.0 Introduction

In this chapter, the intended purpose of the research is discussed. The problem background, aim, specific objectives and research rationale are detailed. The chapter also articulates the research questions to be investigated, innovative aspect of the research and impact on the industry. It ends with an outline of the thesis, with a summery of what is contained or found in each chapter.

1.1 Problem Background

The obvious technological, political, economical and social leaps particularly emanating and happening in the USA, Europe and Japan in the past couple of decades has impacted on the standard of living of great many people around the globe through manufacturing (Clark and Fujimoto 1991; Warnock 1996). From a political/ economical point of view, this is evidenced in a wider industrial-economic growth, competitiveness and attractiveness to foreign direct investors, while from the consumers' perspective is mirrored in diversified and sophisticated customer tastes and expectations, lower product prices, better quality of products, wider varieties and a faster and better service (Goldman *et al.* 2004). However, from a historical point of view, it is not merely the product, but rather the methods of their production that shapes the history of cultures (Warnecke 1993). The way the evolution of production techniques (EPT), features and factors affecting key aspects of manufacturing development are viewed and investigated is of great significance both to the economy and general well being of the people.

Today's market environment is synonymous with an ever increasing pace in production, decreasing product cycle times and an increasing shift from mass production to mass customization (Sharifi and Zhang 1999; Paolucci and Sacile 2004). Broader product ranges, shorter model lifetimes, and the ability to process orders in arbitrary lot sizes are the norm in modern day markets (Goldman *et al.* 1995). In more recent times, market meltdowns, economic downturns, bankruptcy, government bailouts, wars and global warming have all impacted on the growth and performance of important individual industries and market-economic sectors.

The model of traditional manufacturing was based mainly on mass production principles and designed for long-term, high-volume production of only a few products (Babiceanu *et al.* 2005). This structural hierarchical architectural system is suitable for batch production in a steady state, but not for small batches in a dynamically changing environment (Ryu and Jung 2003; Shin *et al*, 2008). Then came the quest for more variety, lower costs and superb products quality and changes in customer expectations which places a huge demand for more dynamic and flexible scheduling approaches requiring frequent re-scheduling based on the current system status e.g. changes in production orders and resource availability (Babiceanu *et al.* 2005), which require not only efficiency of production but also flexibility and responsiveness (Brennan and Norrie, 2003). Traditional and conventional manufacturing methods are failing to stand to these challenges because they offer hierarchical, inflexible, centralised solution incapable of coping with dynamic manufacturing environments in part because of fully or partially centralised decision making process (Shin *et al.* 2008; Heragu *et al.* 2000), with poor fault tolerance to unexpected events and uncertainties (Frayret *et al.* 2004). As a result, the focus is now on external dynamics of industrial processes and how to handle manufacturing complexities in an unpredictable, customer-driven market. New manufacturing architectures and strategies must be introduced to make the transition from traditional hierarchical and rigid system to decentralized and flexible frameworks in such highly dynamic environments (Paolucci and Sacile 2004). The 21st century manufacturing demands offering choices to customers, which in turn requires low-volume high-variety product, dynamic shop floor reconfiguration to meet new requirements, an agile environment to respond to changes and new demands quickly (Deen, S. M., 2003; Katayama and Bennett 1996). Rapidly changing economy and impatient customers pushes enterprises with a dynamically changing paradigm. Prices are plunging with delay, product lifecycle is getting shorter with substitution, and competitors are everywhere and ever-changing. In these circumstances, adaptability to change, time to market and agile operation are not an optional property but requisite for survival.

To sustain a pro-active manufacturing capability and overall competitive market conditions, (Kadar *et al.* 1998) proffer that one key part of the solution is the management of uncertainty, complexity, and disturbance. There is also a compelling need in industry for sound and precise techniques for process restructuring (be they administrative, technical, or support processes) (Vernadat, F., 1996). To this end, (Kadar *et al.* 1998) think that a distributed, multi-agent manufacturing architecture exposes viable choices to hierarchical, rigid and centralised solutions offered by the traditional manufacturing system. One advantage of this perspective is that it provides reactive capabilities, to help cope with uncertainties and nonlinearities arising as a result of complexities from products to be manufactured and processes (Wiendahl and Scholtissek, 1994). To meet these challenges, (Ryu and Jung 2003), suggest that emerging manufacturing systems should be (1) intelligent, autonomous and distributed system with independent function models and (2) Flexible, reconfigurable and easily adaptable to uncertainties (Ryu and Jung 2003).

It is imperative to establish novel manufacturing systems, with capability to proactively perceive the environment and autonomously adapt to changing environments (Shin and Jung 2007). According to Bongaerts *et al.* (2000), while a strict hierarchy results in rigid behaviour in response to changes and disturbances, a loose and flexible hierarchy can bring out predictability and opportunities for more optimising in a dynamically changing environment. To meet the need of such an unpredictable environment, the manufacturing system of the day should be equipped with an open, reconfigurable and scalable organisational structure (Shin *et al.* 2008).

Few manufacturing philosophies have been suggested to bridge the gap left by the traditional manufacturing system. These include; Agile manufacturing (Gunasekaran 1998, Sharifi and Zhang 2001), Biological or bionic manufacturing system (BMS) (Okino 1992, Okino 1993, Ueda 1992, Ueda 1993, Ueda 1997b, Ueda 2001a), Holonic manufacturing system (HMS) (Seidel *et al.* 1994, Valckenaers *et al.* 1994, Van Brussel et al. 1998, McFarlane and Bussman 2000), Fractal manufacturing system (FrMS) (Tirpak 1992, Warnecke 1993, Venkatadri *et al.* 1997, Ryu *at al.* 2000, 2001, Ryu and Jung 2002) and responsive manufacturing (Gindy *et al.* 1996, Saad and Gindy 1998).

FrMS, amongst these emerging manufacturing systems is at the center of this study. It is based on autonomous, cooperative agents called fractals. The FrMS is renowned for its dynamically configured hierarchy consisting of recursively constructed self-similar entities.

FrMS conceptually proves and promises a viable option in tackling 21st century dynamic manufacturing concerns. It provides flexibility, adaptability, agility, and dynamic re-configurability (Deen, S.M., 2003), which core requisites are needed to face new industrial needs as well as providing lean and agile requirements. The fractal manufacturing solution has the afore-mentioned attributes, with independent functional modules as essential, key components (Ryu and Jung 2003).

1.2 Purpose and justification

This research sets out to develop a novel and revolutionary architecture using Fractal company concept to enable manufacturing enterprises make rapid, informed and balanced decision in forming short/ or long term relationship in a supply network. This architecture helps leverage their positions to react more effectively to erratic customer attitudes and fast evolving of technology while responding more robustly to uncertainties and fluctuations in a supply network.

1.2.1 Specific objectives

The principle objectives of the research are to investigate this futuristic manufacturing method in detail including its implementation and applicability and juxtaposing this with traditional, more mundane manufacturing models. Its specific objectives are enumerated below and will include;

a) identifying the features and structural characteristics of fractal enterprise as an emerging approach to maximise the logistical attribute of a lean manufacturing systems and to provide the strategic merging of engineering network capabilities and high level of responsiveness.
b) exploring the potentials of this novel partnership, where suppliers become assemblers within the enterprise' facility, with a view to maximising the benefits of the partnership.
c) identifying the general requirements for developing the necessary tools for fractal modelling, monitoring and controlling of the networked enterprises, to facilitate the implementation of the proposed architecture.

1.2.2 Innovation

What is revolutionary in this research is the use of "FRACTAL company" concept to form hands-on collaboration between enterprise and their key suppliers. The suppliers co-own the business as assemblers of their own components within the enterprise's facility. This is a complete U-turn from the orthodox 'supply and leave' and will provide the desired environment to integrate the product design and production planning and enhance operational communications. Fractal concept is an open-ended network system provider with self-similarity by means of having common enterprise goal. Integration of the limitless fractals companies are essential to build up a holistic network system with identical or even common goals/ aims (Warnecke 1993). It is anticipated that the inherent ability of the fractal network system will yield improvement through the self-organising control loops. This implies that fractals are free to choose their own potential and optimising methods of problem solving provided that the results are reliable and fulfil the requirements and responsibilities.

1.2.3 Anticipated benefits and impact on industry

a) There is improved design for manufacture, as the supplier is directly responsible for assembly of their own modular components.
b) There is also less emphasis on fire fighting, since there is a reduction in inventory and more emphasis on process improvement.
c) Operating in an information enriched environment, there is improved communication with suppliers leading to faster product development and improved respons-

iveness.

d) The new approach will lead to leaner manufacturing systems and reduction in excessive management.

1.3 Research questions

This research is centered around three key questions. These questions form issues which are addressed in the course of this research.

Question 1.

What are the distinguishing features and structural characteristics of the fractal manufacturing system amongst other 21st century emerging manufacturing systems?

Question 2.

What are the potentials and feasibility of the fractal manufacturing partnership (FMP), where suppliers become assemblers while co-owning the enterprise' facility?

Question 3.

How will this novel alliance be maximized to boost and encourage logistical attributes of lean and agile manufacturing capabilities, improve communication and reduce excessive management?

There will be challenges and barriers facing this new approach and how industries in the 21st century should accept and trust open-book relationship to succeeding as integrated partners.

1.4 Research focus

The research centres on the basic idea of the fractal which is the creation of self- regulating organisational work groups, each within its own area of competence. This configuration aids a synergic collaboration between enterprises and their key suppliers and supports a decentralised, holistic organisational structure leading to a network of integrated, leaner virtual enterprises (Noori *et al.* 2000, Parkinson, 1999). The coordination of the input and output values of the fractal is achieved by superimposition of computer assisted information and communication system (Warnecke 1993).

1.5 Outline of the Thesis

The thesis is composed of nine chapters in total. Though wholly integrated, each of these chapters describes and implements a fundamental component of the research. Each chapter discusses a milestone in the research and launches the study logically into the next key element. It is intended that the reader can locate and identify any aspect of the study quickly and easily.

1.5.1 Chapter 1 - Introduction

The introduction of the research is made in this first chapter. Intended purpose of the research is discussed. The problem background, aim, specific objectives and research rationale are detailed. The chapter also articulates the research questions to be investigated, innovative aspect of the research and impact on the industry. It ends with an outline of the thesis, with a summery of what is contained or found in each chapter.

1.5.2 Chapter 2 - Literature Review

In this chapter, an account of what has been published by accredited researchers and scholars on the subject of manufacturing systems; both recent and not so recent is made. The purpose is to convey what knowledge and thoughts have been established on manufacturing systems including their strengths and weaknesses, how relevant, appropriate and useful these are. The chapter starts with the historical development of manufacturing and manufacturing systems and their progression till the turn of the 20th century and beginning of the new millennium. The Challenges of manufacturing going forward is also summarized. The chapter then progresses with the traditional manufacturing methods, highlighting why it has failed in the 21st century. It ends with juxtaposing the emerging manufacturing systems for comparative studies, addressing the research gaps and validating the research questions.

1.5.3 Chapter 3 - Research Methodology

The analysis of the nature of the research presented in this chapter enables the positioning of the research against a continuum of research techniques and the selection of the most appropriate methods deployed in solving the problems. Initially, the chapter devices a methodology for the research project, then it deploys this in answering the research questions. It then presents the various mathematical tools, techniques and methods used in achieving the set targets. It also presents a clear and concise overview of basic principles and available computing techniques for carrying out enterprise modelling and integration.

1.5.4 Chapter 4 - Fractal architecture in manufacturing

In this chapter, an extensive investigation of the subject of Fractal and the fractal manufacturing system is made. Initially, the fractal concept is described, tracing its origin, geometry and characteristic features including the fractal specific characteristics. The chapter progresses with presentation of the Basic Fractal Unit (BFU) which is the main component of the fractal system, the functional modules, and the subject of fractal manufacturing layout. The chapter ends with the fractal manufacturing system, a clear and concise distinction between the traditional manufacturing system and the fractal system. Then a critique of the traditional system is made to show why it has not seen the light of day in the 21st century.

1.5.5 Chapter 5 - Designing the Fractal Enterprise

The fractal shop floor layout described in chapter four is designed in this chapter using the genetic algorithm approach, paying attention to determination of capacity level, cell composition and flow distances. Initially, the chapter discusses the general fractal layout design requirements including the aggregate steps. Then a general treatment of the Genetic Algorithm (GA) approach is made. Progress is made with the application of GA to the proposed design of FrMS shop floor layout and implemented using MATLAB. The chapter ends with discussion of the result and final conclusions.

1.5.6 Chapter 6 - Fractal Supply Chain

The fractal internal design made in chapter five is at the core of the fractal enterprise. This dealt with fractal cell design which is at the grass root of the fractal manufacturing system. In this chapter, the fractal principle is applied in developing the Fractal supply network. Lean manufacturing system is presented, describing the origin, importance and key elemental components. The chapter progressed with the integration of lean with agility which had already been examined in chapter two, in the 'leagile' concept. Supply chain reference models are presented next looking at different examples. Finally, a brief case study of Johnson Inc. is made to illustrate the concept of 'leagilty' and the chapter is concluded.

1.5.7 Chapter 7 - The fractal Manufacturing Partnership (FMP).

Management of total supply chain presented in chapter six is readily apparent in this chapter. The modelling and simulation of the integration of OEMs and their key suppliers is made, maximizing lean and agile network capabilities. For a start, an elaborate discussion of partnerships and close collaborations between OEMs and suppliers is made, highlighting the advantages as well as the shortfalls. This is closely followed by the description of the system to be modelled. The chapter makes progress with the modelling of the FMP proper which is implemented using Arena. The analysis of the output performance statistics and inferences are made. Then the chapter closes with the conclusions.

1.5.8 Chapter 8 - Supplier selection in FMP.

The success and realization of the FMP modelled in the last chapter (chapter seven) hinge critically on quality and reliable suppliers. Selection of tried and tested suppliers to go into the FMP is made in this chapter. This is carried out using the Analytical Hierarchy Process (AHP) approach. The supplier selection process is defined and described for a start. Then the buyer - supplier relationship is differentiated from OEM - supplier alliances. The analytical hierarchy process is then presented, making the mathematical formulations and assumptions. Modelling the supplier selection using the AHP is carried out and implemented using MATLAB. The model results and discussions are made. The chapter is then concluded.

1.5.9 Chapter 9 - Conclusions, contributions to knowledge, limitations and further works

This chapter draws concluding remarks, summaries and generalization of the research. It addresses various achievements of the project. The key, original contributions of the research to knowledge in the area/ field of manufacturing are placed in perspective, articulated and set against the research questions as well as the main aims and key objectives of the research and how far these targets have been satisfied/ met. The chapter ends with suggestions and recommendations and further works.

Chapter Two

2.0 Literature Review

In this chapter, an account of what has been published by accredited researchers and scholars on the subject of manufacturing systems; both recent and not so recent is made. The purpose is to convey what knowledge and thoughts have been established on manufacturing systems including their strengths and weaknesses, how relevant, appropriate and useful these are. The chapter starts with the historical development of manufacturing and manufacturing systems and their progression till the turn of the 20th century and beginning of the new millennium. The challenges of manufacturing going forward are also summarized. The chapter then progresses with the traditional manufacturing methods, highlighting why it has failed in the 21st century. It ends with juxtaposing the emerging manufacturing systems for comparative studies, addressing the research gaps and validating the research questions.

2.1 Historical development and progression of Manufacturing

The 18th century was popular for the transformative effect of division of labour engineered by proto-economist Adam Smith. Huge benefits were brought by trade in the 19th century highlighted by David Ricardo. He gave lessons detailing about comparative advantage; when two economies interact, they both can benefit even if one is more advanced across the board. Michael Porter made great insights into industry clusters in the 20th century.

There were series of significant changes early on in the 20th century manufacturing environment, as transformation happened from traditional labour-intensive manufacturing to automated systems in North America (Hopp and Spearman 2000). Precision jigs and repetitive flow techniques made the first steps towards mass production possible. Stationary assembly lines were first used at Oldsmobile motors in 1903. Cadillac followed in 1908 with its introduction of part inter-changeability (Mahoney, R. Michael, 1997, Mathias 1983).

Around 1911, the basic concepts of industrial psychology were beginning to be formulated and studied (Chase and Aquilano, 1992).

In 1913, the introduction of one of the greatest technological innovations -the moving assembly line with interchangeable parts was made for the manufacture of Ford automobile (Sipper and Bulfin, 1997, Chase and Aquilano, 1992). This evidently slashed the assembly time/ labour significantly. Shortly afterwards, in 1914, activity scheduling charts were introduced and this led to the application of economic lot size model for inventory control in 1917 (Duguay *et al.* 1997). The impact of the First World War was creeping in and was felt in no small measures. Significant among major changes that impacted on manufacturing developments at this time included the redrawing of the map of Europe and the opening of trade to the east. Rationalisation of production was popular in these years aiding and encouraging mass production. The positioning of specialised machines according to process flow requirements was also well known. Rationalisation led to product layout where machines were arranged so that products followed some routing (Doll and Vonderembse 1992). Set-up and balancing tasks was well suited to the idea of high-volume as opposed to scheduling and this helped manufacturers realise important economies of scale (Mahoney, R. Michael, 1997, Chase and Aquilano, 1992).

In the years 1927 to 1933, the famous Hawthorne study threw a whole new light on factory-worker motivation. The study revealed that changing the level of illumination, for instance had much less effect on output than the way in which the changes were introduced to assembly workers. Reduction in illumination in some instances led to increased output.

Sampling inspection and statistical tables for quality control were beginning to emerge around 1931. In 1939, the complex problems of logistics control and weapons-system design, during world war 11 (WW11), provided stimulus for the development of the inter-disciplinary, mathematically oriented field of operations research or OR. It brought together practitioners in such diverse fields as economics, mathematics and psychology. These specialists customarily formed a team to structure and analyse a problem in quantitative terms so that a mathematically optimal solution is obtained (Chase and Aquilano, 1992).

At the conclusion of WW11, in 1945, the Japanese were beginning to come up with interesting strategies which were focused on low labour costs (Womack *et al.*1990, Mahoney, R. Michael, 1997). At this time, they manufactured cheap products with infamously poor quality. Internationally, there were less competition, and manufacturers focused on production efficiency rather than customers and this was the norm (Chase and Aquilano, 1992). In the 1950s and 1960s, extensive development of OR tools of simulation, waiting line theory, decision theory, mathematical programming, computer hardware and software, project scheduling techniques of program evaluation and review techniques or PERT, and cost per thousand (CPM). Quality began revolutionizing in Japan in the late 1950s. It became the key to obtaining competitive advantage through quality centres, referred to as Poka-Yoke (Mahoney, R. Michael, 1997). Later in the 1960s, small and medium scale machining centres began to consider the idea of distant supervisory control. Hence the first Computer Numerically Controlled (CNC) machines were made, giving manufacturing systems more flexibility, with reputable quality. Within this period, Japanese companies responded to increased demand for their quality products, through large capital investments in their infrastructure to exploit the consequence of economies of scale using volume-focused factories, and later in the mid 1960s began introducing variety to their customer base.

The 1970s heightened the complexity in coordinating production systems especially with large batch industries. Small-batch sector production relied on stand-alone machines. The need to keep manufacturing operations under control through standards became more imperative than ever. This heralded the crusade for computers and the material requirements planning (MRP) and manufacturing resource planning (MRP11). The development of a variety of computer software packages to deal with routine problems of shop scheduling, inventory, layout, forecasting, and project management and rapid growth of MRP, and enterprise resource planning (ERP). This became a big breakthrough for manufacturing because it helped in production control. The program evidently enabled production planners to swiftly adjust production schedules and inventory purchases to meet changing demands for final products.

The Japanese used group technology, design for manufacturability and assembly, Just-In-Time, JIT - an integrated set of activities designed to achieve high-volume production using minimal inventories of parts that arrive at the workstation 'just in time', and Taguchi's design of experiments between 1975 and 1985 to effectively reduce costs and improve delivery performance (Womak *et al.*, 1991). They dominated the automotive industry through moving from mass production to lean production systems. Their lean strategy focused on high performance goals, such as zero defects, declining costs, high flexibility and more product variety that are in direct alignment with current customer requirements. They focused on the importance of eliminating inventory and other forms of waste, increasing flexibility in production scheduling, reducing lead time and enhancing levels of quality (product and customer service). Late in the 1970s and early 1980s, there was the development of the manufacturing strategy paradigm. This work by renowned scholars and academics emphasized how manufacturing executives could use their factories' capabilities as strategic competitive weapons. It identified the ways production management can be analysed as strategic and tactical decision variables. It also raised the need for making trade-offs among such performance measures as low cost, high quality, and high flexibility in designing and managing factories (Womak *et al.*, 1991, Chase and Aquilano, 1992).

The 1980s brought the idea of work flow coordination, carried out by a central control computer (Korem, Y., 1983, Vernadat, F., 1996, Waldner, J.B., 1996). This gave birth to the extensive use and application of JIT, total quality control (TQC), which sought to eliminate causes of production defects, and factory automation (CIM, FMS, CAD/CAM, and Robotics etc) (Korem, Y., 1983, Singh, V., 1997, Waldner, J.B., 1996). The computer was intended to perform functions like scheduling jobs, downloading instructions on how to make parts or send instructions to automated vehicles, robots or machines (Singh, V., 1997). The concept of 'Cell' and computer integrated manufacturing (CIM) centres, were emerging, where raw materials or sub-assemblies, were manually or automatically (using an automated storage and retrieval system (ASRS)), loaded at the initial station, and from here a computer took control of the process. On completion, the job is removed and passed to the next process. Later on, from a technological point of view, it was observed that the CIM had several drawbacks, because of its somewhat excessive rigidity and centralisation. Though these types of jobs are more prominent in metal shop floors (turning, milling, drilling, sheet work etc.), while many other less automated processes were left isolated (Vernadat, F., 1996). Nevertheless, even in the metal-mechanic industry, with much more application of CNC machines, comparatively little output could be achieved due to high inflexibility (Korem, Y., 1983, Singh, V., 1997). The early 1980s also saw the introduction of mass production in the service sector, though quality and productivity represented challenges to service firms. From 1985 in Japan, a time-based competitive strategy ensued (Womak *et al.*, 1991). The central focus was to create a system in which value-added time as a proportion of total time is maximised throughout the entire value delivery chain. Quality function deployment or QFD, a disciplined system was invented for translating customer requirements into company requirements all the way through product development to the factory floor.

2.2. The Consortium for Advanced Manufacturing (CAM-I.)

By the beginning of the 1990s, the availability of low cost computers helped increase productivity and reduce time in build-test-redesign iterations. Tools like drawing, finite element analysis, simulation software and rapid prototyping systems increasingly gained popularity. The trend now was how to bring manufacturing companies to a world class status, through benchmarking and promotion of best practices. Lean strategies, Total quality management (TQM) and continuous improvement became more fashionable, bringing processes under a coherent and consistent performance (Oliver *et al.* 1994, Spear and Bowen 1999).

By the turn of the 20th century, from 1995 to 2000, multinational efforts were raised to promote concepts and systems against a fast-paced advancement in technology in the new millennium. Under several projects, the consortium for advanced manufacturing international (CAM-I) and the intelligent manufacturing systems (IMS) developed reports dedicated to the Next Generation Manufacturing Systems (NGMS). Participants from industry and academics from the world over contributed and formed the framework of NGMS or guidelines towards the emerging manufacturing systems (EMS). CAM-I. affirms that a NGMS needs to be reconfigurable, capable of development, able to manage turbulence, realize changes and evolve into uniqueness. If a MS complies with these pre-requisites, then it will achieve competitive delivery time, quality and cost, and obtain satisfactory profit margins. Although CAM-I. stated what is expected of a NGMS, it did not mention in specific or categorical terms, in any of its five hundred page report, how this can be accomplished. The 21st century manufacturing has to offer choices to customers, which in turn requires (i) low-volume high-variety manufacturing to handle those choices, (ii) dynamic shop floor reconfiguration to meet new requirement flexibility and (iii) an agile environment to respond to changes and new demands quickly (Deen, S. M., 2003; Katayama and Bennett 1996).

2.2.1. Ideals of the EMS.

These standards have been conceived and proposed as models to be adopted by enterprises for survival, continuity and sustainability in high-paced manufacturing environment as is present in the 21st century. For an enterprise to adopt any EMS, it has to brace up to the challenges and be ready to innovate and evolve to conform to these characteristics, buoyed by a robust structural and organisational savvy. The drivers of these philosophies, according to CAM-I. are shown in (table 2.1) below. They urge and compel the enterprise to move onwards and forwards.

Driver	**Should be**
Main driver	Customers
Other drivers	Stakeholders, shareholders
Configuration	Adaptable in response to demands, both internal and external
Suppliers	Integrated in the internal supply chain
Organisations	Networked with internal and external ones, competitors or not
Ecology	Environmentally aware
Changes	Adaptable to rapid changes in existing and virtual or extended environments.
Composition	Small, simple, autonomous, cooperating units, sharing the enterprises goals in an ad hoc internal environment
Resources	Information and knowledge based, human intelligence oriented

Table 2.1 Drivers for a NGMS Philosophy, according to CAM-I.(2000)

Once an enterprise understands the changes needed, the next move is to review the changes inside the producing facility, adjust its strategy in tune with dynamic market, demanding excellence in quality, innovation, cost, throughput, time to market and achievement of overall competitiveness. The next generation manufacturing (NGM) report also demands that all companies will need to pursue four operational strategies. These strategies include; to integrate the enterprise, use human resources intelligently, develop, manage and employ knowledge, and lastly, employ NGM processes, equipment and technology. The report also has ten implementation sub-strategies alongside these that connect the "Big M" manufacturing, the work of the whole enterprise, with the "little M" of shop floor operations. (Jordan and Michel 2000) elaborated on these implementation sub-strategies of the NGM defining the important sets of actions that companies should take to connect and harmonise their operations. A new generation manufacturing system will require the tools illustrated on (table 2.2), recommended by CAM-I.(2000).

Modelling and simulation	**Robust control technology**
Methodologies/tools to support the establishment, maintenance and change of virtual concepts	Including intelligent ways of communicating
Human- integrated manufacturing	**Scheduling**
Tools for managing the learning process in virtual environments	That pursues self-optimisation in each process and cooperates with others to obtain a harmonious system

Table 2.2 Tools for a NGMS Philosophy, according to CAM-I.(2000)

The ability to develop, manage turbulence, realise changes, evolve into uniqueness and reconfigure if need be are key requirements according to CAM-I., to sustain a competitive advantage and for obtaining satisfactory profit margins, buttressed by an increased awareness in lean manufacturing methods (Sousa *et al.*, 1999, Zaremba and Morel, 2003).

Factor	Characteristics
Product	Concept, development time, technology needed, complexity, customer's perception, how innovative is.
Manufacturing processes	Technology, complexity of production, decoupling point, volumes and mix batch sizes, lead times.
Supply chains	Amount and types of suppliers involved, position in supply chain, after-market needs, distribution centres, transport, inventory, lead times.
Market	Degree of competition, market fragmentation, market opportunities.
Customers	Expectations, segmentation, loyalty.
Enterprise	Size, type of organization, resources available, degree of specialization, ownership, stakeholders, geographic advantages.

Table 2.3 Factors to consider before designing a NGMS (From Kidd 2000)

Shen et al (2000) worked on distributed manufacturing systems and compiled additional set of requirements that NGMS should embrace, shown below on (table 2.3).

A high degree of self-organisation, characterized by systematic disposition, is both a pre-requisite and a paramount significance when enterprises adopt and adapt to the emerging

Requirement	How it should work
Enterprise integration	Integration of all systems within an enterprise, but also with systems of other enterprises (suppliers, distributors).
Distributed organisational architectures	Functions, knowledge and operations are geographical distributed
Heterogeneous environments	Heterogeneous hardware and software applications.
Human integration	With software and hardware applications.
Co-operation	Co-operation with suppliers, customers and partners.
Open and Dynamic structure	Integrate new systems (or resources) or remove existing systems without stopping the process
Dynamic Organisation structure	Allow different organisation structures and the changing between them dynamically, in order to adapt to the volatility of the global markets
Fault Tolerance	The system must react to the occurrence of disturbances and recover from these disturbances in order to minimize their impacts on the system

Table 2.4 NGMS Requirements, modified from (Shen *et al*, 2000)

manufacturing systems. This frames the new manufacturing constitution and characteristic attitude that paves the way for flexibility and sustained profitability.

2.3 Challenges of manufacturing in the 21st century

The significant changes and advancements, domestically and globally in politics, economics, society and in technological developments in the late 20th century and early 21st century is mind-boggling, and has strong impacts and effects on manufacturing companies (Kuehnle 1995, Kidd 2000). External environmental conditions, market pressures, stakeholder expectations, internal pressures and new strategic paradigms are all contributing factors to this new trend (Taisch, M., and Montorio, M., 2005). Technological leaps in the fields of digital technology, mobile telecommunication and broadband networks have remarkably changed the way things are done and have impacted on the speed and cost of information exchange, the ease of movement of people and goods, and pervade all branches of industry and commerce (Warnock 1996, Featherston 1999). This has fuelled fierce global competition. The basis of this competition is creativity and innovation in all aspects of the manufacturing enterprise, the capability of maintaining market shares and achievement of rapid growth. The information-processing capability to treat masses of customers as individuals is permitting more and more companies to offer individualized products while maintaining high volumes of production (Goldman *et al.*, 1995). While different techniques have been developed for systems and application integration, business integration i.e. global inter-operability, system-wide information/knowledge exchange, and process coordination among intra- or inter-organisational structures still needs a lot of attention (Vernadat, F., 1996). However, improvements and developments in technology (increased power of PCs, open systems architectures, high speed internet, communication and information networks, advanced data exchange formats and protocols, knowledge exchange formats) improvements are already being seen (Vernadat, F., 1996). To compete in a fierce global market, it might be required that companies change their business models and set up businesses across several continents, though this kind of move can sometimes provoke controversy. It might also require distribution of highly competitive production resources and skilled workforce. The final report of the next-generation manufacturing study (NGM, 1997) suggests that manufacturers in the 21st century will have to be distributed worldwide to meet customer demands economically. This trend towards globalization requires decentralization of workforce, and increases the need for fast, accurate, high quality medium of communications. The tough manufacturing world in the 21st century will be dominated by five major themes that include; customer power, time and change, knowledge-based competition, organizing for the best decisions and the challenges of globalisation (Hughes 1997, Clark and Fujimoto, 1991, Nagel and Dove, 1991, Doll and Vonderembse, 1992).

On the other hand, customers are getting involved early on in the production process through electronic means. This is because information and knowledge on all aspects of manufacturing enterprises and the marketplace are instantaneously available in a form that is effectively assimilated. These sophisticated customers, most of whom are in newly developed countries and economies demand products that are customized and tailored to their specific needs. They call all the shots and their demands are also getting increasingly dynamic, diverse and unpredictable (Ryu and Jung 2003, Jordan and Michel 2000).

The broad survey conducted by the committee on visionary manufacturing challenges (Committee report on VMCs 1998), of the National research council's board on manufacturing and engineering design identified the major challenges that will face manufacturing enterprises in the first quarter of the 21st century and the enabling technologies to overcome them. The study is a two-part Delphi survey designed to forecast manufacturing challenges and among other things, they identified six "grand challenges" or fundamental goals that need attention and considerable changes (NRC 1998). These challenges are detailed in (table 2.5) below;

Challenges	**Enabling technologies**
• Achievement of concurrency in all operations - planning, development and implementation, aimed at reduction of time-to-market, encourage innovation and healthy rivalries, and improve quality.	• Technological advancement in systems modelling capability; modular, adaptable design methodologies; adaptable manufacturing processes and equipment; and materials and processes.
• How to integrate human/ technical resources to enhance workforce performance and satisfaction. Development and integration of optimal human and technical resources and people dedicated to speedy response and effective communication with suppliers and parties	• Integrated human-machine interfaces, automated routine functions, new educational/ training methods enabling rapid assimilation of knowledge, robust software for collaboration systems and swift response to customer needs and effective communications.
• How to instantaneously transform information gathered from diverse sources to useful knowledge for making effective decisions, and make this available whenever and wherever it's needed.	• Information technology will particularly help capture and store data. And manufacturing enterprises will be able to 'instantaneously' transform them into useful knowledge.
• Reduce production waste and product environmental impact to 'near zero'. Development of cost-effective, competitive products and processes that do not harm the environment, reduce energy consumption and encourage recycling.	• Proactive participation in the assessment of environmental impacts, the establishment of environmental goals, and the development of technology to meet environmental goals towards sustainability.
• Rapid reconfiguration of manufacturing enterprises driven by rapidly changing customer needs, changing market opportunities, developments in process, product and electronic communications technology.	• Adaptable, integrated equipments, processes and systems that can be readily reconfigured will help build new organisational structures and employee relationships and greater flexibility and integration of activities.
• How to develop innovative manufacturing processes and products towards decreasing dimensional scale. Design and manufacturing of new alternative materials and components.	• Advances in the control of processes and microstructures at submicron scales and the analysis and unlocking of the chemical and biological secrets of nature provides unique insight into processes and chemical make-ups, leading to exciting ways to manufacture, clone, grow, and fabricate a vast array of products. Breakthroughs in nanotechnology and biotechnology will lead the way in innovative processes.

Table 2.5 Manufacturing challenges from Committee report on VMCs

These changes will be driven by the social and political environment, the needs of the market place, and opportunities created by technological break-through.

The Baldrige Foundation, though a quality award giving body, conducted a survey in 1998 of top manufacturing executives. Their findings are in total agreement with the above set of challenges and included a long list of items that worry these manufacturing practitioners currently. Globalisation, improving knowledge management, cost and cycle time reduction, improving supply chains globally all made the list. Also manufacturing at multiple locations in many countries and managing the use of part-time, temporary and contract workers are among the items that concern the manufacturing sector currently (Baldrige Foundation 1998). The next tier of concerns included; developing employee relationships based on performance, improving human resources management, improving the execution of strategic plans, analysis and measurement of organisational processes, developing a consistent global corporate culture, outsourcing of manufacturing and creating a learning organisation. One thing seems clear. The Baldrige survey identifies current concerns rather than anticipated or foreseeable manufacturing challenges in the 21st century.

(Drucker P. 1999) sums it all up in his studies of management issues and challenges for the 21st century in his book, "management challenges for the 21st century". He opined that there is no one best tailor made way to organize a next generation enterprise. The best organisation of a company remains the one that works best now and can evolve and stand the changes of tomorrow.

2.4 Need for robust manufacturing systems

To meet the needs of a high-tech society, rise up to the demands of consumerism and customer power, improve supply chains both locally and globally and reduce costs and cycle times to achieve competitiveness, the development of holistic, flexible and innovative manufacturing methods plays a very visible role. The manufacturing enterprise must not only tackle the production process from all angles - product ordering, product design, production and sales but also develop proactive, innovative, process technologies (Jordan and Michel 2000, Ryu and Jung 2003). To sustain competitive market conditions, (Kadar *et al.* 1998) proffer that one key part of the solution is the management of uncertainty, complexity, and disturbance. To this end, they think that a distributed, multi-agent manufacturing architecture exposes viable choices to hierarchical, rigid and centralised solutions offered by the conventional/ traditional manufacturing paradigms. One good side to this is that it provides reactive/ proactive capabilities, to help cope with uncertainties and nonlinearities arising as a result of complexities from products to be manufactured, processes and in the company structural organisation (Wiendahl and Scholtissek, 1994). To meet these challenges, (Ryu and Jung 2003) reason that newer manufacturing systems should be (1) intelligent, autonomous and distributed system with independent function models and (2) Flexible, reconfigurable and easily adaptable to uncertainties (Ryu and Jung 2003, more references). They have to be reinvented in the pursuit for strategies that work with less resources, providing satisfaction for market demands, promptly and consistently (Womack et al. 1998).

2.4.1 Hierarchical Vs Heterarchical control systems

The traditional control architectures of manufacturing systems have centralised and hierarchical models, which are unable to cope with dynamic environments because of their rigid structures and fully or partially centralised decision making process (Shin *et al.* 2008, Heragu *et al.* 2002). Their response to unexpected events is slow and they have poor fault tolerance (Frayret *et al.* 2004). Though hierarchical control is easy to understand and has less redundancy, it is significantly deficient in sensitively affecting all levels in the hierarchy. And since it is not easy to flexibly reconfigure the shop layout, it can not cope with the ever-changing customer needs (Ryu and Jung 2003; Shin and Jung 2007). Conversely, the heterarchical, decentralised control architecture is more flexible and responsive to dynamic environments. However, they still present their own problems in the form of a limited global optimisation and predictability of behaviour due to a completely distributed structure (Babiceanu and Chen 2006). Hybridisation of hierarchical and heterarchical models (Heragu *et al.* 2002) exploits the good aspects of both optimising and handling dynamics and eliminates the bad features. The structural hierarchical control of computer integrated manufacturing (CIM) systems is suitable for batch production in a steady state, but not for small batches in a dynamically changing environment (Ryu and Jung 2003; Shin *et al*, 2008). This is because the prevailing concept of CIM of the 1980s has to evolve to face new industrial needs for better customer satisfaction, global economy, reduced time-to-market, lean and agile manufacturing, and coordination of business processes of the extended enterprise (Vernadat, F., 1996).

According to Bongaerts *et al.* (2000), while a strict hierarchy results in rigid behaviour in response to changes and disturbances, a loose and flexible hierarchy can bring out predictability and opportunities for more optimising in a dynamically changing environment.

Various quasi-heterarchical control architectures have been proposed and examined, applying open hierarchies into heterarchical structures composed of autonomous and intelligent decision capabilities (Shin *et al.* 2008). Prominent among studies based on multi-agent structures include MetaMorph (Maturana *et al.* 1999) and MetaMorph II (Shen *et al.* 2000), both agent-based mediator-centric federation architecture, in which resource agents have loose hierarchical relations with mediator agents. PROSA (Van Brussel *et al.* 1998) and ADACOR (Leita˜o and Restivo 2006) based on the holonic manufacturing concept, wherein the hierarchies to be nested as part-whole relations are organised, supposing that dynamic organising is permissible. (Ryu and Jung 2003, Ryu *et al.* 2003a) made their pitch on the Fractal Manufacturing system (FrMS), which is based on fractal-like organisational concept. The FrMS is renowned for its dynamically reconfigured hierarchy consisting of recursively constructed self-similar entities.

2.4.2 Organic, agent-based systems

The quest for a more flexible, more intelligent and adaptable manufacturing system (MS) is leading excitedly to a shift to more organic, decentralised, innovative structures. Distributed or agent-based problem solving considers how tasks or problems can be divided among a number of nodes that cooperate in dividing and sharing knowledge about the problem and its solutions (Kadar *et al.* 1998, Durfee, 1991, Fox, 1994). In the agent-based approach, beside the agents there is the important role of the tasks as parts of a global reactive scheduling (RS) problem (Sycara *et al.* 1991); the objects used by agents to execute tasks; the control that defines the co-operation between agents, the group organisation and its co-ordination problems; and the communication between agents depending on the selected protocol, i.e. the rules that specifies the way to synthesis messages. A distributed system is a collection of agents that can fully represent an organisation (Fox, 1994). Organic systems explore the potential for creating intelligent systems by modelling the behaviours and mechanisms that underlie uncertainties in processes (Deen, S.M., 2003). (Anosike and Zhang, 2000), made a proposal in which they presented a conceptual hierarchically structured multi-agent architecture. In it, each agent has the ability to perceive and evaluate changes that occur in the manufacturing environment, interact with other agents in the system in order to reach an optimal decision, and act based on that decision. They also respond in a timely way to unexpected changes on actual shop floor situations. Agent-based manufacturing methods and technologies have proved a viable option in tackling 21st century dynamic problems. Based on autonomous, cooperative agents, they provide flexibility, adaptability, agility, and dynamic re-configurability (Deen, S.M., 2003). Ryu and Jung (2003) are the first to admit that a successful manufacturing solution must have the afore-mentioned attributes with independent functional modules as essential, key components. Hierarchical disaggregation or decomposition of shop floor activities using agent-based technologies has been applied as a control model for implementing computer integrated manufacturing (CIM) (Ryu and Jung 2003). In it a central machine takes charge of working out schedules and controls of the shop floor. Though still an important research area, these agent-based manufacturing systems offer a major challenge as they have to deal with both logical and physical objects. For example, in the event of a malfunction, a logical object can be logically discarded from the operational environment and the software itself restarted. But with physical objects, they will be inspected by human beings for damage and physically removed from the operational environment (Deen, S.M., 2003). Overall breakthrough in agent-based attempts is leading interestingly to more robust/ flexible solutions that are better in terms of quality, implementation, cost, fault tolerance, and adaptability to changing environment. These fault-tolerant and robust alternatives essentially have self-repair and self-replication capabilities.

2.5 The Traditional/ Conventional manufacturing systems

Manufacturing involves complex integration of activities/ processes such as; process development, product design, plant design, capacity planning and management, product distribution, plant scheduling, quality control, workforce organisation, equipment maintenance, strategic planning and global distribution of products known as supply chain management (Hopp and Spearman 2000, Chase and Aquilano 1992).

The methods of manufacturing referred to as 'Traditional or conventional manufacturing systems', used for the transformation of raw materials into finished goods, are those production concepts introduced immediately following the Second World War to meet a high demand for low-cost standardised products (Sipper and Bulfin, 1997, Doll and Vonderembse 1992). They are characterised by and known for maintaining relatively high levels of raw material (stock), work-in-process, and finished goods inventories as a hedge against uncertainty in supplier delivery and quality, production rates and quality, and customer demand (Dyck, H. *et al.* 1988). (Warnock, I., 1996) calls this attitude, 'the traditional strategic misconception', because manufacturing was seen simply as an operating function to produce the goods that sales and marketing had wanted. The economies of scale associated with mass production were achieved by large extensively automated factories with complex organisational structures (Jin-Hai *et al.* 2003) and there was myopically more focus on production efficiency rather than the customer (Brennan and Norrie, 2003). As a result, mass production of high-quality, standardised goods and efficiency of production was the norm. Scheduling was done rigidly prior to production using static solutions (England, 2004). Information on when each product is to be processed, on which machine and the order are all included in the production schedule (Hopp and Spearman, 2000). Then came the quest for more variety, lower costs and superb products quality and changes in customer expectations which places a huge demand for more dynamic and flexible scheduling approaches requiring frequent re-scheduling based on the current system status e.g. changes in production orders and resource availability (Babiceanu *et al.* 2005), which of course makes the former approach obsolete. As a result, efficiency of production alone was not enough. Flexibility and responsiveness joined the key benchmarks for world-class manufacturing (Brennan and Norrie, 2003). (Figure 2.1) shows how demand management, resource requirement planning and aggregate production planning are based on long-term decisions performed at the highest level of the production and control hierarchy. The issue here is that planning requires an estimated forecast of the future product demand, calculation of the level of capacity required to meet this demand in a cost-effective manner and the specification of the optimal combination of production rates, workforce levels, and inventory holdings to meet expected fluctuations in the demand (Wild, 1993). This model of traditional manufacturing based mainly on mass production principles and designed for long-term, high-volume production of only a few standardised products makes it unable to cope under dynamically changing circumstances (Brennan and Norrie, 2001, Maione and Naso, 2001), lacking the flexibility required to weather the storm in this dynamic environment e.g. frequent changes in process requirements and production orders (Koren *et al.* 1998; McCarthy and Tsinopoulos 2003). The high structural rigidity and deterministic rather than flexible decision making approach (Heragu *et al.,* 2002) makes it incapable of coping in such random and uncertain production environment (Sluga and Butala 2001) called by the quest for more variety, lower costs and superb quality products. It also offers a hierarchical, and centralised solution incapable of coping with dynamic manufacturing environments in part because of fully or partially centralised decision making process (Heragu *et al.* 2000; Heragu *et al.* 2002; Kadar *et al.* 1998; Shin *et al.* 2008), with poor fault tolerance to unexpected events and uncertainties (Frayret *et al.* 2004). The inability to respond to changes timely and cost effectively is top on the major issues facing manufacturing enterprise (Anosike and Zhang, 2000). Market changes e.g. variations in demand patterns, variations in product mix, shorter product life cycles etc. induce further changes to the manufacturing enterprise.

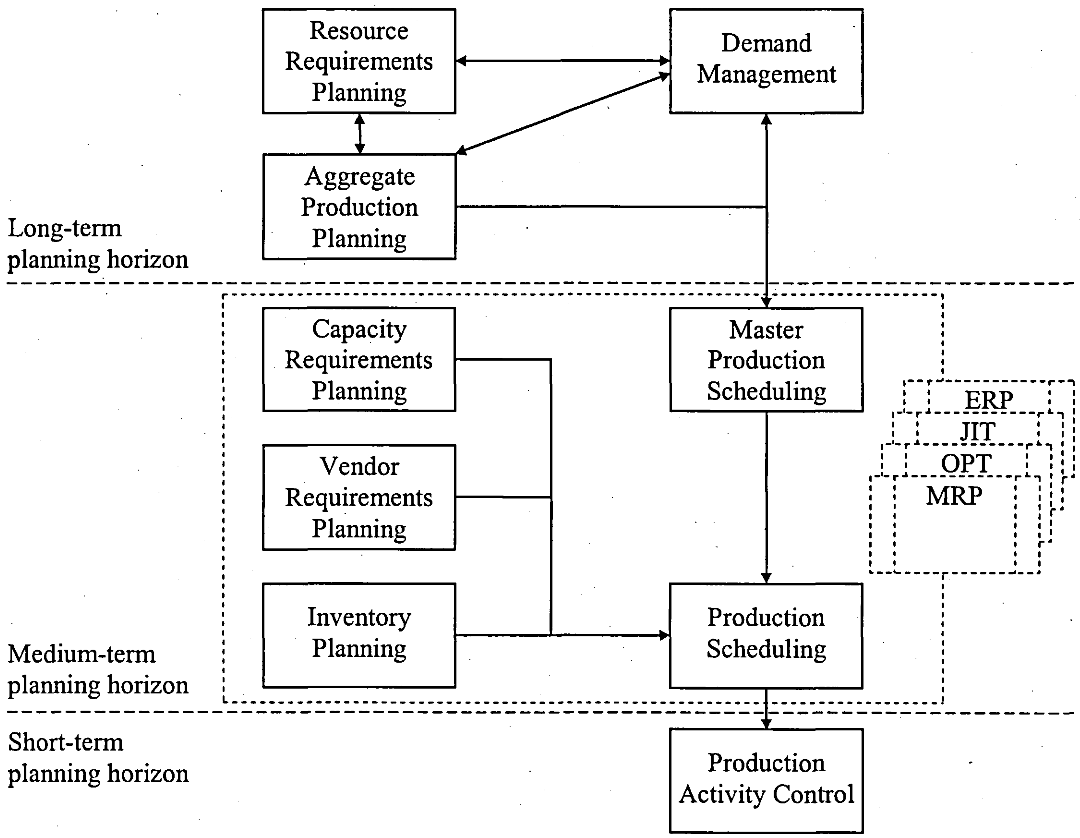

Figure 2.1 Production planning and control framework (From England 2004)

Valckenaers (1994) categorised these changes into "Production Change" and "Production Disturbance". A Production Change is an alteration to the production condition which is intentionally performed by the plant. This includes the introduction of new products or new product variants, increase (or decrease) of production capacity, introduction of new production technology and changes in the work force. A Production Disturbance is an unanticipated change to production conditions with negative effect on the process performance. This is classified into External and Internal Disturbances. External disturbances include those caused by customers (e.g. variations in demand patterns) and those caused by suppliers (e.g. the ability or inability to deliver raw materials of the right quality and quantity at the right time). Internal Disturbances include equipment failures, quality miss, lack of co-ordination and work force unavailability. In order to respond timely to these changes, manufacturing systems should be Reactive, Scalable, Flexible, Agile, Self-motivated, Informative and Self-Organising.

The advent of factory automation systems - CIM, FMS, CAD/ CAM in the 1980s marked a significant improvement to conventional manufacturing approaches and the way enterprises are integrated (Vernadat, F., 1996, Korem, Y., 1983). Material requirements planning (MRP), enterprise resource planning (ERP), manufacturing resource planning (MRP2) etc are manufacturing and production planning and control systems that integrate inventory systems and scheduling more efficiently in a stable manufacturing scenario (England, 2004). These traditional manufacturing planning and control systems are renowned for their rigidity, hierarchical structures and lack of swift response to uncertainties and disturbances (Ramasesh *et al.* 2001, Bongaerts *et al.* 2000, Wang, 2001). The CIM uses integrated systems and real-time data communication through digitization to improve organisational and human resources efficiency (Korem, Y., 1983, Singh, V., 1997). These are applied to direct control and monitoring of all process operations including; design, analysis, planning, purchasing, cost accounting, inventory control and distribution with factory floor functions i.e. materials handling and management (Korem, Y., 1983). Even CIM system is not without its own challenges. Among key concerns to development of the CIM system are; ease of integration of components from different sources, the integrity of communication data and total process control (Vernadat, F., 1996, Waldner, J.B., 1996, Korem, Y., 1983). Warnecke (1993) warns that mutual dependencies and influences amongst the structures of organisations and systems will not make it any easier to design CIM environments. It should involve detailed network management. He therefore suggested that particular attention be paid to the following:

- Model language paradigms e.g. object oriented and agent concepts which support the systematic aspects of the organization.
- User openness and transparency in CIM systems.
- Expert-system supported information gathering and compression
- Provision for evaluation via simulation prior to the execution of expensive operations
- Knowledge-based process scheduling, execution and control systems
- Intelligent control mechanisms providing short feedback loops between decision maker and real process.

Hierarchical decomposition of shop floor activities is commonly used as a control model for implementing CIM systems. Hierarchical control of CIM systems fits batch production in a steady state, but is not feasible for small batches in a dynamically changing environment due to its insensitivity in all levels of hierarchy. Hence it can not handle the ever-changing customer demands, since the hierarchy control architecture is inflexible in reconfiguring the shop floor (Ryu and Jung 2003). The key characteristics and differences between conventional manufacturing system and computer integrated manufacturing system are enumerated in (table 2.6) below.

Conventional manufacturing system	**CIM System**
• Repetitive manufacturing- products are assembled in volume from standard options. • Feeding processes (fabrication) are performed by job shop manufacturing (work centres). • A job shop- a department or a work centre which is formed by grouping similar machines together. A work centre produces different items usually in large lots. • Assembly is done on assembly line. • A large work-in-process inventory - to absorb changes in production variables • Push manufacturing approach - the first work station starts an order and it has no relation to what is needed in the following work station. • Primary tool: Division of work (Taylor's theory) • Workers have limited training and understanding of the production process (focused on their own work centre). • Managers don't get involved in designing, planning, organizing the operations.	• New environment that supports a real-time environment that moves faster. • A technological change that deals with flexible manufacturing cells and systems, a hierarchy of controls that tie everything together, and the management information system. • Increased manufacturing flexibility. • Variations in routing, operations, machines and operators. • All three functions of management are affected: planning, implementation and control (Change is required throughout the organization). • Absence of large inventory. Cycle stock is small. Safety stock is not used. • Pull manufacturing approach - producing the exact quantity when needed. • Primary tool: Team-based technology. • Degree of freedom- used in controlling the system and to react to unpredictable events: Machine failures, absence of operators, changes in the workshop environment. • Multifunctional workers (trained in different skills) involved in the process control; have responsibilities and authority to make decision on issues.

Table 2.6 The difference between conventional systems and CIM

The newer, emerging manufacturing systems are conceived and formulated to herald the shift from highly centralised description to a decomposed or segmented manufacturing paradigm. The structure so formed paves the way for a flexible and robust model needed to tackle the challenges of the 21st century (Kodali *et al.*, 2004), and more importantly bridge the gaps left by the traditional manufacturing system.

2.6 The Emerging manufacturing systems (EMS) - A comparative study

It is established that the traditional manufacturing system falls short of the capabilities needed for faster response to changes, transforming operations, organisation and technology at much shorter notice etc. which requisites are imperative and directly impact on product choice, price, quality and delivery (Tharumarajah, A. 2003, Kadar *et al.* 1997, Gunasekaran 1998, Katayama and Bennett 1999, Sharifi and Zhang 1999). To meet these requirements will need the ability to adapt and respond to changes in the environment, construct and reconstruct in response to changes in product demands and technology offerings while creating new market opportunities (Tharumarajah, A., 2003, Katayama and Bennett 1999). The next generation manufacturing system should be; (1) an intelligent, autonomous, and distributed system with independent functional module and (2) it must be flexible, highly configurable, and easily adaptable to a changing environment in nature (Ryu and Jung, 2003). A promising structure would be organic and very similar to a conglomerate of distributed and autonomous units (Tharumarajah, A., 2003). These units while self-determining their actions communicate and cooperate with others to carry out the expected actions and pursue goals both individually and as a group (Kadar *et al.* 1997, Tharumarajah, A., 2003). The multi-agent structure replaces the highly centralized database and control system with a network of agents with local databases and advanced communication capabilities. The overall system performance is not globally planned, but develops through the dynamic interactions of agents in real time (Van Dyke Parunak, H., 1996).

Some control and organisational architectures and philosophies have been proposed and studied in a distributed manufacturing system paradigm as models for future manufacturing system and to bridge the gap left by the traditional manufacturing system. Among these are: Agile manufacturing (Gunasekaran 1998, Sharifi and Zhang 2001), Biological or bionic manufacturing system (BMS) (Okino 1992, Okino 1993, Ueda 1992, Ueda 1993, Ueda 1997b, Ueda 2001a), Holonic manufacturing system (HMS) (Seidel *et al.* 1994, Valckenaers *et al.* 1994, Van Brussel *et al.* 1998, McFarlane and Bussman 2000), Fractal manufacturing system

(FrMS) (Tirpak 1992, Warnecke 1993, Venkatadri *et al.* 1997, Ryu *at al.* 2000, 2001, Ryu and Jung 2002). These philosophies were first proposed around the periods shown in (figure 2.2 below). Treatment of the Agile Manufacturing system, Holonic manufacturing system and Bionic manufacturing system has been made here. A full treatment of Fractal manufacturing system is made in chapter four. They have many conceptual, promising perspectives and advantageous features (Saad, S., and Aririguzo, J., 2007), yet have been known to be difficult in implementation (Ryu and Jung, 2003). (Figure 2.3) also shows the approximate time span expectancy for full implementation of these paradigms.

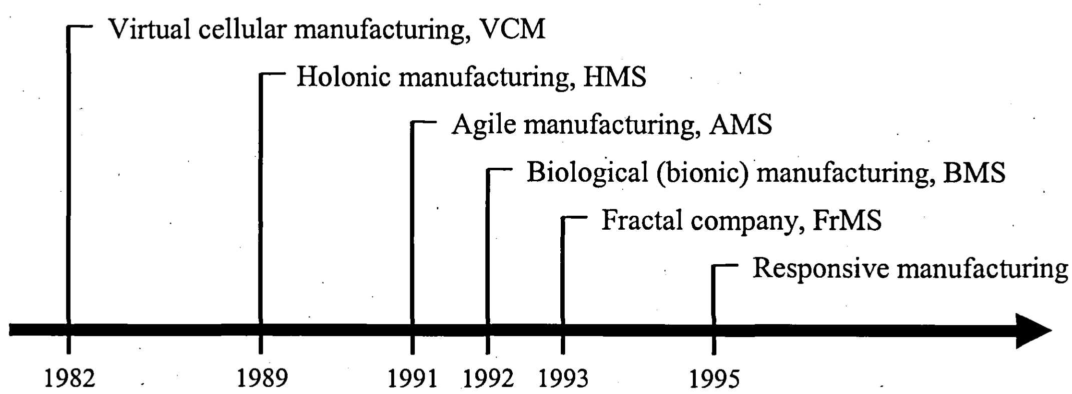

Figure 2.2 Imprecise year of introduction of philosophies and their origin

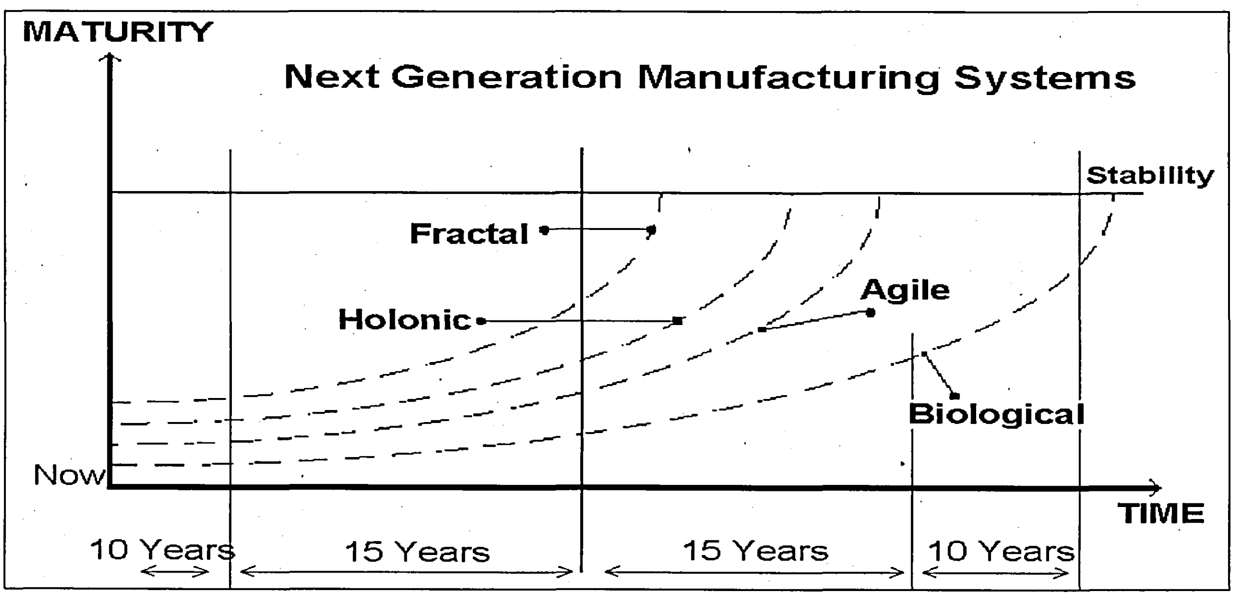

Figure 2.3 Time span expectancy for mature implementation

2.6.1 Agile Manufacturing (AMS)

One of the first attempts on the agile manufacturing subject was made by the Iacocca Institute in 1991. It's been seen as an improvement (Mason-Jones *et al.* 2000b) or a step further in the evolution of the lean manufacturing paradigm in production methodology (Parkinson, S., 1999, Richardson, 1996). Agility or agile manufacturing is defined as the use of market and a virtual corporation to exploit profitability opportunity in a volatile market place (Naylor *et al. 1999,* Mason-Jones *et al.* 2000a and 2000b). It aids companies in the face of uncertainty in an unpredictable, ever changing environment (Cho *et al.,* 1996) as well as provision of the ability to pro-actively tackle uncertainty ahead of competitors whose responses are purely reactive (Mason-Jones and Towill, 1999, Goldman *et al.*, 1995). Emphasis is on the design of a complete enterprise that is flexible, adaptable, and has the ability to thrive in a continuously changing business environment where markets consist of rapidly changing 'niches' serving increasingly sophisticated customer demands. Goldman *et al.* (1995) suggest four underlying agile components; delivering value to customer, being ready for change, valuing human knowledge and skills and forming virtual partnerships. (Figure 2.4) below shows core agile characteristics according to (Yusuf *et al.*, 1999), means towards successful exploration of competitive bases - speed, flexibility, innovation, reactivity, quality and profitability. These are mainly lean manufacturing attributes. However, forming virtual partnership distinguishes agile manufacturing. This is because, according to (Parkinson, 1999), agile organisations share information with key customers, extending throughout the supply chain to key suppliers and distributors, thus finishing with a network of organisations

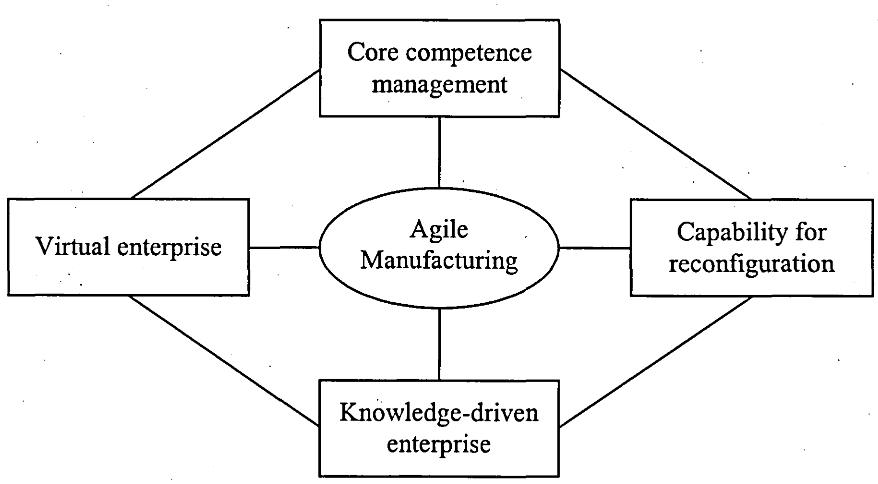

Figure 2.4 Core attributes of Agile manufacturing (Yusuf *et al.* 1999)

(or one large, virtual corporation) and a 'web' of information in which each contributes the information required for all to understand the entire picture. This "information enrichment" is not only desirable but obligatory (Mason-Jones and Towill, 1999). It is aided by the development of manufacturing support technology that allow marketeers, designers and production personnel to share a common database of parts and products, share data on production capacities and problems, in particular where small initial problem may have large "downstream" effects (Parkinson, 1999). The attributes above are in complete agreement with their earlier studies, (Goldman, 1994) which portrays agile manufacturing as comprising the characteristics of lean production, extended to encompass four basic principles - products are solutions to customers' individual problems, virtual organisations are formulated where products are brought to market in minimum time through internal and external cooperation, entrepreneurial approaches are adopted so that organisations thrive on change and uncertainty, and knowledge based organisations are formed which focus on distributed authority supported by information technology. This scenario creates flexible or virtual organisations to meet customer expectations and for entering niche markets rapidly and meeting specific customer demands (Robertson and Jones, 1999). Jin-Hai *et al.,* 2003, in the same vein noted that agility creates a unified electronic network to facilitate; (i) swift response to uncertainty (ii) building and enhancing of core competencies (iii) supply of highly customised products (iv) synthesis of diverse technology (v) intra-enterprise and inter-enterprise integration. Sharifi and Zhang (2001) put forward a conceptual model to explain agility. The model shown on (figure 2.5) below helps to realise the strategic and operational benefits of the AMS.

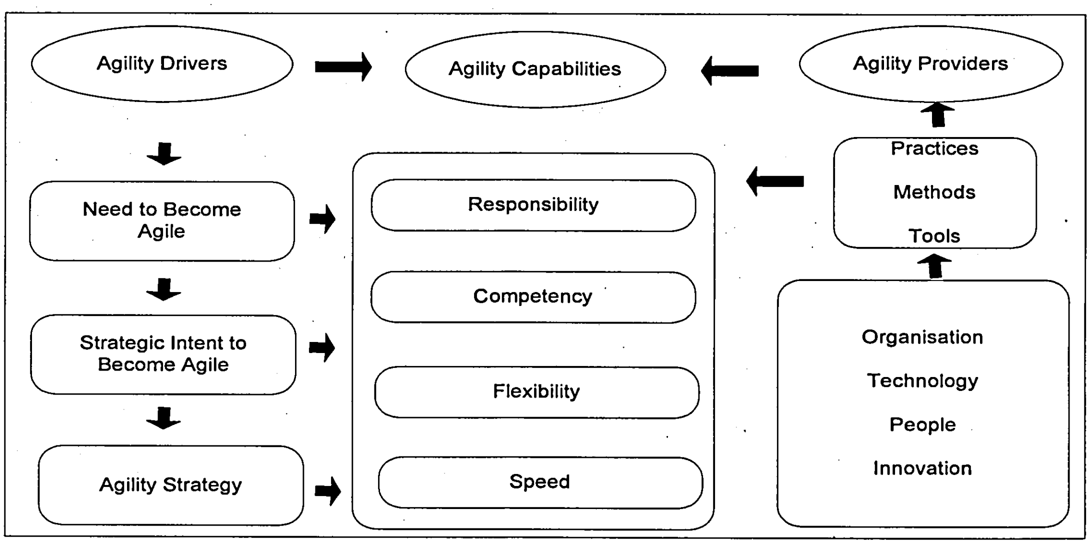

Figure 2.5 Agility concept (Sharifi and Zhang 2001)

An agile manufacturing system (AMS) has the ability to produce unlimited variety of goods, handling high production volumes at the same time, with low costs and within short periods of time (Fujii *et al.,* 1996, Büyüközkan *et al.,* 2004). (Shewchuk, 1998 and Tang and Qiu, 2004) referred to this as the ability to produce with quick, easy and changeable resources. Brown and Bessant, (2003), think AMS is a brand of Mass customisation, where there is the ability to produce unlimited variety of products in small quantities, according to very specific customer requirements. Maskell (1996, 2001) saw agile manufacturing as a system which deals with uncontrollable matters. On the other hand Kidd (2000) identified an agile system as a strategy, "quick moving, nimble and active", concerned with objectives, structures, processes and resources, paying attention to the organisation as a whole (Brown and Bessant, 2003). Truong and Thomas, (2005), launched a proposal where factories, in order to survive, must be lean, agile and sustainable, converting into a "fit manufacture". The authors referred to AMS as an ability to prosper in a sustainable manner through the manufacture of high quality products facilitated by an integrated, robust, highly responsive and reconfigurable lean manufacturing system and reduced internal and external manufacturing cost.

In accordance with the definition given by the Agile Manufacturing Enterprise Forum (AMEF), the design of an agile manufacturing system is characterized by features as shown below in (Table 2.7).

Feature	Should be
Greater product customisation	Allows manufacturing-to-order implemented with a relatively low unit cost.
Speed	Rapid introduction of new or modified products
Products	Upgradeable products that allow easy disassembly, recyclables and reconfigurable
Processes	Dynamic reconfiguration of production processes, made possible by a high level of line flexibility and reconfigurable

Table 2.7 Features of an AMS, according to AMEF

(Celano *et al.,* 2002) considered that technology, strategy, people and systems are the main elements to focus on when an AMS is under construction. Daghestani (1998) proposes a model to design an AMS, which takes into account the environment for manufacturing, and depends on the volume, variety, production time per unit, demand period and length of the life cycle of each product.

In terms of the operational aspects of the AMS, Hormozi (2001) identified infrastructure that need to be developed prior to the successful operation of an AMS. According to his research, governmental regulations have to be in tone with rapid changes to cope with an agile environment. This will help in streamlining the operational functions of the enterprise i.e. customer order and delivery process, product development, production process, and supplier network. Potential agile businesses should consider the guides shown on (Table 2.8). True agility should ideally extend flexibility back to product design and new product introduction through such techniques as rapid prototyping (Robertson and Jones, 1999).

Operational Key	**Description**
Cooperation	Virtual enterprises where customers, suppliers, and third parties should be brought together, e.g. in the design of a product
Technology	As a device to share data: linking external systems into the organisations: customers can place orders automatically to the plant and then the plant can schedule, and feed back accurate delivery dates to customers. V.G., internet and other tools, allow the customer to have a simple and standard link to make inquiries, send message, and specify their needs
Organisation	Radically rethink processes and implementing organisational organic arrangements, internal cooperation where departments must work together for their common goal looking always towards the clients. Leadership, motivation, and trust replace the management style of command and control.
Employee Flexibility	Employees need to be encouraged to embrace continuous change, to adequately address their customers changing and focused needs. Employees must be trained and empowered within a clear vision of company' principles and goals.
Quality	Quality and high levels of service are expected, pretty much a part of the agile approach.

Table 2.8 Operational issues in an Agile Enterprise based on Kidd (2000)

Sharifi and Zhang (2001) developed an analytical tool to define qualitative drivers needed to define the level of agility that might achieve a specific strategy or directional model. They suggested the use of virtual cells for improving volume flexibility (Figure 2.6).

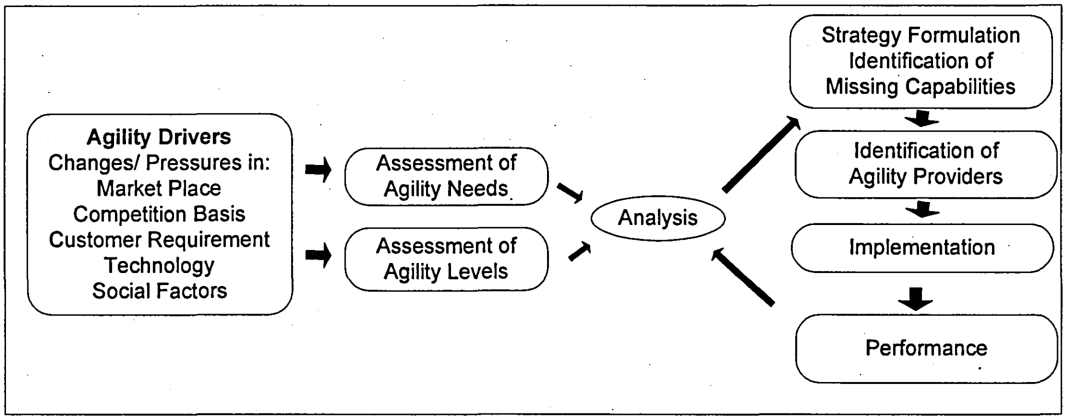

Figure 2.6 Methodology for agility proposed by Sharifi and Zhang (2001)

Control in an agile organisation is somewhat complicated and allows enterprises to gracefully recover from disturbances coming from inside or outside, often with the aid of a multi-hierarchical structure. It also has the ability to cope with uncertainty, and recovers quickly and effectively from any disruption. (Anosike and Zhang, 2002), proposed and presented flexible and robust control architecture for an AMS., shown below on (figure 2.7). This architecture is able to accommodate both homogeneous and heterogeneous agents. These agents are able to perceive and evaluate changes that occur in the manufacturing environment, interact with other agents in the system for optimal performance. They also respond in a timely fashion to unexpected changes by continuously co-ordinating their activities and allocating manufacturing resources dynamically based on actual shop floor situations. (Qaqish, *et al.*, 2003), analysed potential gaps in the supply chain. They studied technology implementation and integration, knowledge management and finally an integrated agile system. Tsai and Sato (2004), proposed an interesting universal modelling scheme for planning, scheduling and procurement with ERP and MRP tools but under certain differences and rules such as the earliest due date policy for scheduling, allowing to create an agile model. This model is still in the implementation stages. (Celano *et al.,* 2002) proposed a model for scheduling based on a line optimiser. (Zhang *et al.,* 2000) accomplished a proposal with a multi-agent system. They dealt with the control with "consultations" between these agents, with different tasks in the system. Other noteworthy studies include (Yusuf and Burns, 2003), which applies the usage of artificial neural networks and the proposal by Gaafar and Masoud (2005), which developed a comparison between genetic algorithms and simulated annealing,

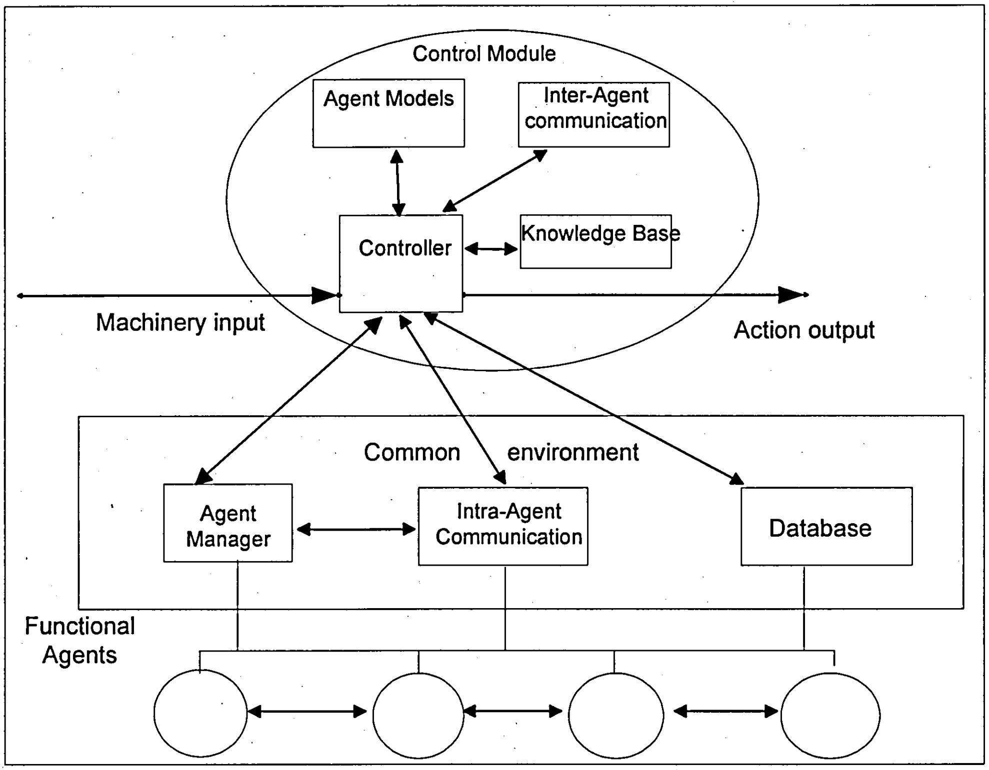

Figure 2.7 A generic Agent Architecture (Anosike and Zhang, 2002)

for an agile single machine in order to minimize the make span, and probes how the simulated annealing is more helpful than genetic developments. A collection of agile architectures is presented on (table 2.9) below. Despite the promising perspectives of these architectures, there is still the problem of how to organize the distributed entities.

Architecture	**Year**	**Strongest Characteristics**
METAMORPH	1996	Multi-agent: integrates design, planning, scheduling and execution Distributed intelligent open environment with a hybrid autonomous approach
AARIA		Designated to demonstrate that agents are feasible for manufacturing solutions with MRP and MES functionality Interface with customers and suppliers
MASCADA	1999	Focuses on manufacturing execution systems Uses local intelligent agents
HOLOS/MASSYVE	1994/ 1999	Multi-agent dynamic scheduling Negotiation techniques Dynamic formation of manufacturing resources Virtual framework for suppliers and customers
B-LEARN	1999	Intelligent supervision for robots assembly cells Integrates dispatching, diagnosis and error recovery Capabilities of learning techniques for recovery and diagnosis
DEDEMAS	2000	Mechanism for decentralized decision making and scheduling Multi-site operations with a virtual approach

TELECARE	2000	Remote supervision based on intelligent mobile agents Redundancy in case of net failure
COMME AGATHE	2001	Multi-skilled and experienced team Uses a unified modelling language Uses existing architectures and communication frameworks Uses Web-based mechanisms, CORBA and XML
OOLO	2002	Model for scheduling in a line with object oriented programming Details database management and buffering
RCCS*	2002	For reconfigurable cell systems Multi-agent architecture with generic agents The architecture resembles the physical cell
APPCS*	2004	For planning, job scheduling, procurement and production control ERP and MRP logic Models abstractions of concepts with a complete simulation
VCIM*	2004	Parallel processing in a multi-agent architecture Java environment implementation Accessible to Small and Medium enterprises

Table 2.9 Examples of agile architectures

2.6.2 Holonic Manufacturing System (HMS)

The term "Holon" describes the nature of "wholes" and "parts". The term was coined by (Koestler, 1967), from Greek word "holos", which means whole; the suffix 'on' refers to a particle or part. He attempts to describe the general principles of open hierarchical systems and concept of holons (Tharumarajah, A., 2003), an entity that has capability of functioning as a self-contained *whole*, while at the same time acting as a *part of a whole* in a hierarchically ordered system (Tharumarajah, A., 2003; Tharumarajah *et al.*, 1998; Sousa et al, 1999). This system has both self-assertive and integrative tendencies, enabling it to evolve to meet changes in its environment by creating stable and self-reliant dynamic hierarchical structure. These two opposing tendencies; the self-assertive, is the dynamic expression of a holon's wholeness, and the integrative, is the dynamic tendency of its 'partness', manifest themselves as autonomous and cooperative attributes. The concept of holons was applied in manufacturing by Suda (1989, 1990), who discussed the dynamic organisational structure of a highly automated Holonic Manufacturing System, including people as key processing part of a Holon to accomplish the overall view of a HMS. (Tharumarajah *et al.* 1996) asserts that a holon is simultaneously a whole (e.g. a machine) and a part of the whole (e.g. a manufacturing system) and has both autonomous and cooperative characteristics, as illustrated on (figure 2.8) below. The holonic concept transfers the benefits such as stability facing disturbances, adaptability and flexibility when dealing with change and efficient usage of available resources to manufacturing. However, holonic characteristics like self-configuration, re-usability and adaptability add advantageous features to manufacturing. Holons cooperate with their lateral partners to combine their competencies and to achieve both individual and system goals (Sousa *et al.*, 1999). The performance of holons is defined by fixed set of rules called canons, that determine their static structural and functional configurations and flexible strategies that define the holons' authorized activities in accordance with the changes in the environment (Tharumarajah *et al.*, 1996), and to help counterbalance the twin attributes of autonomy and cooperation (Tharumarajah, A., 2003). HMS has developed working definitions (Seidel and Mey, 1994; Seidel *et al.*, 1994) of the holonic concept. The HMS Consortium propounds the holonic system as a system that "integrates the entire range of manufacturing activities from order booking through design, production, and marketing…", and is comprised of autonomous and cooperative elements, including technological resources, people and communication networks for resource sharing. Van Brussel *et al.* (2004) defined a holon as "an autonomous and co-operative building block for transforming, transporting, storing and/or validating information and physical objects". This is illustrated as shown in (figure 2.9). Hence a Holon has data processing as well as a physical processing part. Numerous models of their application in manufacturing have been

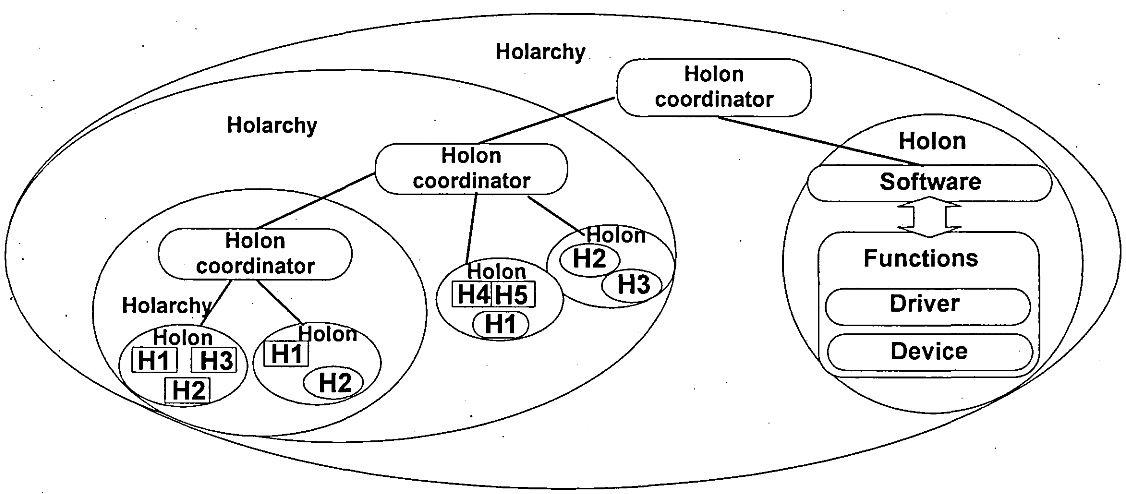

Figure 2.8 The holonic architecture (adapted from Kotak *et al.* 2000)

proposed, ranging from conceptual to practical models and these explore both architectural and operational aspects. Amongst these are models aimed at creating solution for high variety and variable lot manufacturing, through a highly decentralised architecture, built with a modular mix of autonomous, cooperative and intelligent elements (Valckenaers *et al.*, 2001, Brennan and Norrie, 2001, Van Brussel *et al.*, 2004, Norrie and Lin, 2001).

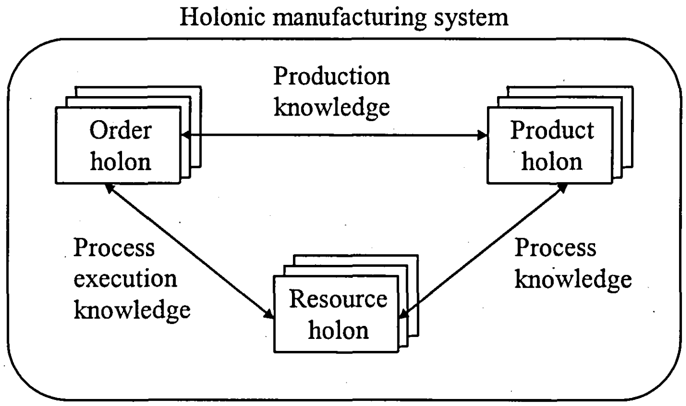

Figure 2.9 Structure of the holonic manufacturing system (van Brussel *et al.* 1998)

Christensen (2000) viewed HMS as the application of value-adding transformations to raw materials for goods production, within a new structure of functional units, and integrating the system's interfaces with its environment. Design of the HMS takes into account two pronged architectural aspects depending on whether the model is single or multi-level structured (Tharumarajah, A., 2003). Without hierarchical ordering, the model looks like the machining cell in (figure 2.10) below. This represents a holarchy comprising diverse characteristics of the system; namely, machining -cell holarchies. Specifying the holon takes a functional or manufacturing view, representing entities capable of generic functions such as scheduling, planning, execution and monitoring (Agre *et al.* 1994; Heikkila *et al.* 1997; Heikkila *et al.* 1967; McFarlane *et al.* 1995) and entities such as machines and parts that have embedded capabilities to plan and schedule (Guo *et al.* 1994; Guo *et al.* 1998) respectively. Coordination can be in-built (Tharumarajah and Wells, 1997) or separated in a specialized coordinator holon (Guo *et al.* 1994; Guo *et al.* 1998; Ng *et al.* 1996). A multi-level structured holon has a number of hierarchically ordered levels, as exemplified in figure 2.10, showing different member holons, which in turn contain member holons and so on. A HMS global architecture (Fletcher and Deen, 2001) is proposed with a set of generic holon types and cooperation blocks to provide the mechanism for constructing holarchies or "compound holons". There is also a manufacturing-specific multi- level model called the PROSA architecture that is built on four basic holon types; a resource holon (e.g. machine), product holon, an order holon and staff holon (van Brussel *et al.*, 1998). Investigation into a more practical operational aspect has focused mainly on strategies for cooperation and contracting for scheduling tasks among competing manufacturing holons (Guo *et al.* 1998; Ng *et al.* 1996; Sousa and Ramos, 1998; Tharumarajah and Wells, 1997).

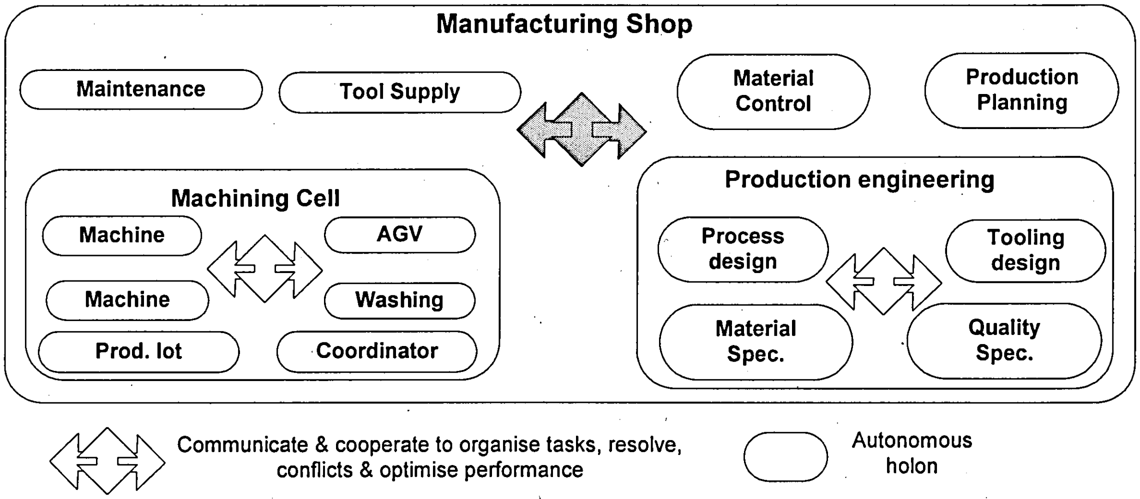

Figure 2.10 A holonic manufacturing shop (Tharumarajah, A., 2003)

Other significant works on the holonic system include; Cheng *et al.* (2004), who accomplished the construction of an abstract object model based on domain knowledge. They designed a HMS specifically for the semiconductor industry (Cheng *et al*, 2004), and (Schaffer and Sieverding, 2000) followed suit for the V-type car engines manufacturing plant. (Babiceanu *et al.*, 2004), drew attention for their material handling systems. Also worthy of note is (Fletcher and Brusey, 2003) packaging system and of course shop floors planning and design (Fischer 1999, Toh *et al,* 1999, Cheung *et al,* 2000, Balasubramanian *et al*, 2001). According to the IMS, an architectural concept for Holonic Control Systems is the Intelligent Control System Model (ICS) (Seidel and Mey, 1994; Seidel *et al.,* 1994). This model described an architecture where unified elements are inter-linked to a gradable system, where intelligent elements are bound in a communication network. Deen (2000) proposal focused on a computational model with a specified behaviour for all its operational states. A structure for intra-Holonic communications that aids this proposal was created by Kremer and Norrie (2000), who designed a series of protocols for messaging between Holons, programming them as a causal-relation sequence with Petri Nets. Kremer and Norrie (2000) also stated that real time functions are needed because of the huge variety of control platforms in heterogeneous, distributed control systems. Fischer (1999) designed an agent based Holonic architecture named InteRRap, where a hybrid model helps to tackle down complexity in a system. In the same vein, Wullink *et al.* (2002) developed holonic architecture for planning and control called EtoPlan, used for handling information processing.

2.6.3 Biological Manufacturing System (BMS)

The biological or bionic manufacturing system is inspired by nature. Similar biological inspirations include design of a burglary detection system, which imitates the senses of pit viper snakes and application of biological knowledge in robots design and construction. The first proposals on the biological manufacturing system were made by Ueda, K., (1992) and Okino, N., (1992). Later Vaario (1996) suggested an "evolution" concept for design of assembly lines. Others like Bozinovski and Bozinovska (2002) worked on natural processes like biosynthesis addressing a natural JIT process. All of the above aim to draw a parallel or transfer the flexibility and adaptability, autonomous and spontaneous behaviour, and social harmony as found in natural forms to industrial operations (Tharumarajah *et al.* 1996). Tharumarajah *et al.*, (1998) ventured into an imitation of the chemical and biological process of a biological cell in a manufacturing system. The design of the BMS is somewhat worthy of note. Tharumarajah *et al*, (1998) acknowledged there is potential in copying biological structures in the design of a Manufacturing System, especially in relation to autonomous and spontaneous behaviour, self-development and social harmony within hierarchically ordered relationships. For instance, a biological cell normally manages a complex set of biochemical reactions. Demeester *et al.,* (2004) established a comparison between some elements of a biochemical reaction with some manufacturing elements (Table 2.10), and Tharumarajah *et al*, 1998, draws a comparison between biological cells and manufacturing units (Figure 2.11).

Biological elements	Manufacturing elements
Biochemical pathway	Production line
Enzymes	Machines
Proteins, Oxygen, Intermediates	Sub-assemblies or Final products

Table 2.10 Parallelism between manufacturing and nature (From Demeester *et al.,* 2004)

(Tharumarajah *et al*, 1996 and 1998; Sousa *et al*, 1999) affirm that the cell is the basic unit of all biological structures, and ascends to tissues, organs, lives and society in a hierarchical order. They all have similar structures but different and multiple operative functions. The stability and regulation of the chemical environment where the cell exists is maintained by enzymes and hormones respectively (Tharumarajah *et al*, 1998). In manufacturing this corresponds to production units on the shop floor which operates autonomously as illustrated on (figure 2.11). These units perform operations by obtaining the inputs from the shop floor, and return outputs back to the environment. Tasks are specified in a top-down process, while the units' actions at the lower levels support the operation of the whole system in the bottom-up process (Tharumarajah *et al.* 1996).

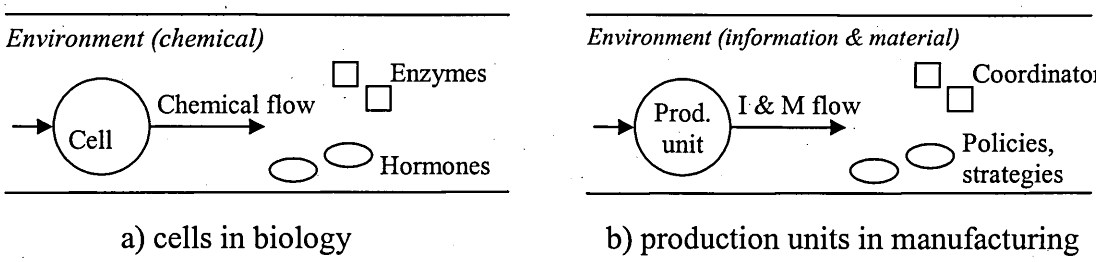

Figure 2.11 Similarity of cells in biology and manufacturing units (Tharumarajah *et al.* 1998)

Biological systems according to (Ueda *et al.* 2000) are remarkably known for their ability to adapt to environmental changes and to sustain their own life through functions such as self-organization, self-recognition, self-growth, self-recovery, learning and evolution. To achieve this objective, organisms make use of two types of biological information - genetic information (DNA-type) and individually learned information (BN-type) (Ueda *et al.* 2000). Thus the challenge in manufacturing is the design of an organising process, a "DNA-type", and "BN-type" information and communication system to manufacture products from raw materials, as shown in (figure 2.12). Under this communication system, data is distributed among diverse levels (supra/ sub-modelons), in order to perform an activity. In addition, the notion of enzymes and their role in the living beings is modeled in MS by entities called coordinators or supervisors (Sousa *et al*, 1999; Tharumarajah *et al*, 1998). These entities are very important since they are responsible for the regulation and control of the system. Furthermore, the supervisors also play an organizational and structural role, influencing the modelons relations and imposing self-division or aggregation, to meet requirements imposed by the environment.

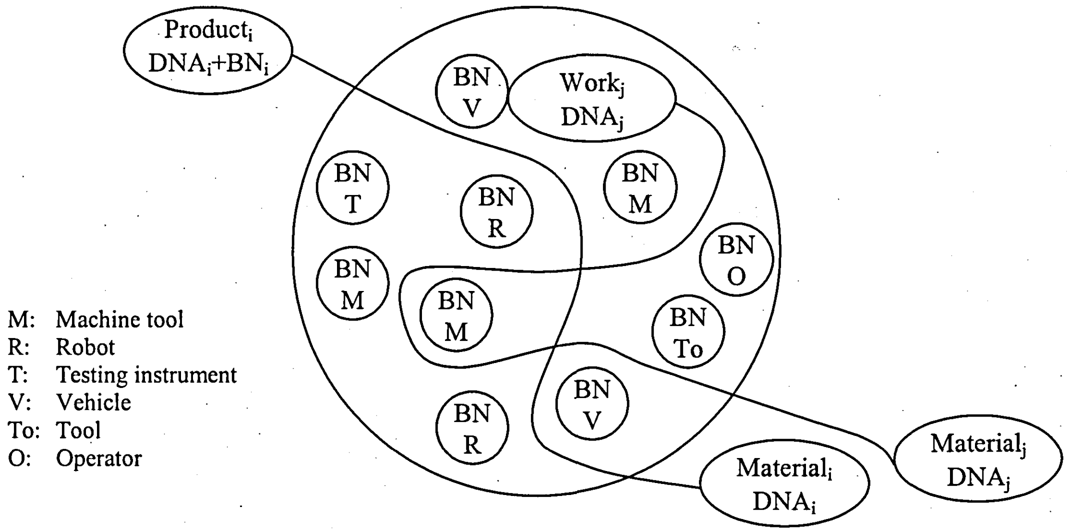

Figure 2.12 Biological information and communication system in BMS (Ueda *et al.* 2000)

Operationally, Demeester, *et al.,* (2004) identified a set of characteristics that organic production systems develop naturally. These are considered fundamental characteristics for the BMS. These include localisation of raw material, customized local production and local recycling loops. There are also remarkable similarities between biological and manufacturing activities as pointed out by Demeester, *et al.,* (2004) on (table 2.11).

Manufacturing operation	Biological operation
Pull system	Reacts to biological processes
Bottlenecks define the throughput	Enzyme reaction determines the entry rate
Lower WIP / Excess capacity	Cell saves as much as possible because of space and degradation of material.
Quality	Key-lock processes to guarantee correct reproduction and reactions: DNA replication, protein creation, etc.
Postponement	Same originating structure can be modified before pathway and split into different products: steroids, amino acids, etc.
Commonality	Usage of four basic blocks: DNA, proteins, polysaccharides and lipids.

Table 2.11 Behaviours in an operational BMS (Demeester, *et al.* 2004)

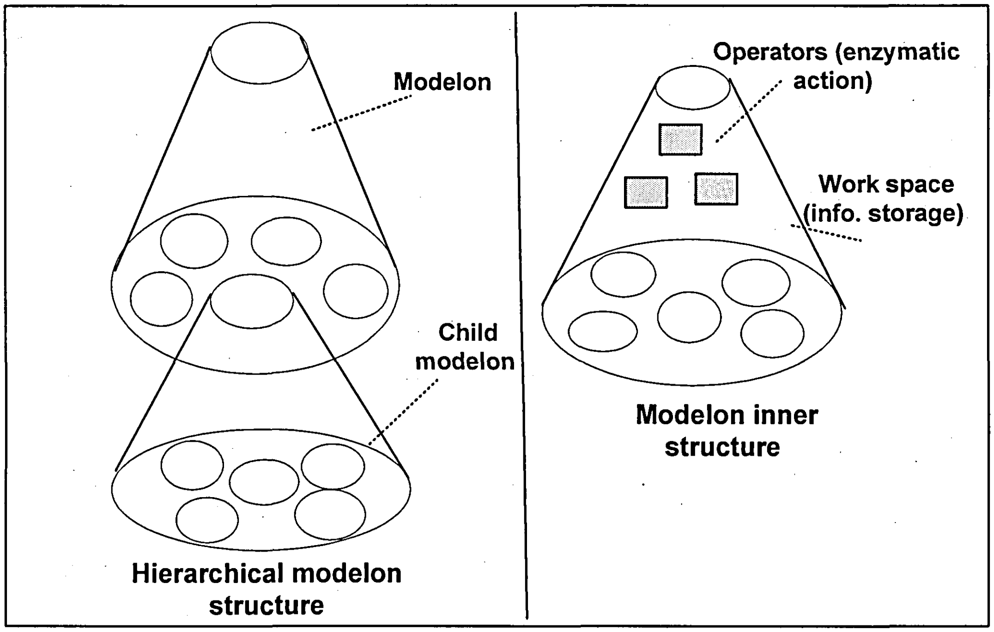

Figure 2.13 Structure of the modelon (From Tharumarajah, A. 2003)

According to the NGMS Project 95002, the BMS architecture could be approached in two ways; either programming a constraint for each modelon, with logical relationships as equalities or predicates, or with an agent-based program. This means that whenever a trigger is set, an autonomous software element will launch a program or predicate which will receive data and send a value for a variable. A different model, besides the DNA language is through neural communication, achieved with distributed application software's like Windows for Distributed Internet Application (Windows DNA), or architectures frames like the Common object request broker (CORBA) (Ünver and Anlagan 2002). The control of the BMS can be reflected in three levels according to the NGMS Project 95002; spatial, functional and in sequence. There has to be a dynamic control over job dispatching, in an ever changing layout facility but allowing a scheduling based on nature. Several of the NGMS project' tasks, under the CAM-Inc auspices, had demonstrated how a prototype manufacturing system based upon biological concepts, could be implemented. Ueda and Imanishi (2000) made a proposal on viewing an automobile chassis line as a Biological product, based on Brain Neuron-type model. Vaario, *et al.*, (2000) proposed a methodology for actually controlling a BMS, through simulation first of a PCB drilling line; and later on with the simulation of a "line-less" automotive welding line. Honda Engineering and Fujitsu replaced a traditional automobile assembly line with an Organic line. In this biological line, intelligent mobile welding robots are attached to an automobile body that is mounted on an automatic guided vehicle (AGV) capable of moving around the shop floor. Both dock up to each other and the robot perform its hundreds of welds as the AGV moves through the shop floor. The most prominent, recent research on biological manufacturing systems has concentrated on realising the self-organising capabilities by proposing dynamic shop-floor configuration (Vaario and Ueda 1996b, 1998b, Fujii *et al.* 1997, Ueda *et al.* 2001b, 2002), reconfiguration (Ueda *et al.* 1997b) and scheduling (Vaario 1996, Ueda *et al.* 1997a, Vaario and Ueda 1998a) methods controlled by a 'self-organisation simulator'. This is aimed at factory operations in real-time by continuously calculating the local potential fields of the machines and transporters on the shop floor (Vaario and Ueda 1998a). According to (Vaario and Ueda 1997) this bottom-up approach leads to a local optimisation with unpredictable global results and enables dynamic and continuous adaptation to disturbances. An application of a biological manufacturing system that had significantly reduced operational costs has been reported by McCormack (2000).

2.7 Comparative study of different EMS concepts

The emerging manufacturing concepts as described above have underlying principles and features depicting a highly flexible manufacturing system, structurally and operationally (Saad, S., and Aririguzo, J., 2007). Overall, the emerging manufacturing systems (EMS) show a parallel relationship or manner. They can be compared in course, identity, direction, and their similarity can also be highlighted. The EMS though having different origins, their structure have essential properties which have overlapping characteristics, in that they share the recursive, whole-part notion, as found in nature such as fractals, living organisms and biological societies. This aids their final objective in forming dynamic systems while maintaining overall orientation and goal (Kodali *et al.*, 2004). Control is represented by procedures applied to maintain operability, integrity and coherence of the system overall. This rapidly becomes more diverse, ensuring suitability, eligibility and providing the structural/ socio-economic opportunities needed in a complex 21st century market, (Zaremba *et al.*, 2003). The main ideas and basic units of these paradigms are summarized in (table 2.12) below. It is discernible that the AMS does not have a basic unit. Agile manufacturing is mainly a managerial concept that provides vision and strategy for future organisations. In place of that, there are enablers which are current design techniques, tools and technologies. The enabler in agile manufacturing facilitates the development of manufacturing support technology that allows the designers, production personnel, and marketers to share a common database of parts and products, production capacities and surrounding problems.

Philosophy	Unit	Paradigm
AMS	______	Creation of policies and processes, tools and training, for quick response to customer needs and a volatile market, while keeping cost and quality in check. A precursor in manufacturing transformation.
BMS	Modelon/ cells	Mimics the harmony in morphology of biological systems (living organism); cells, organs, organism, drawing parallels with the harmony exhibited by such biological mechanisms and realising these essential properties in manufacturing.
FMS	Fractal	Based on the theory of fractal geometry. The basic unit (fractal) contains the characteristics of the entire manufacturing structure, integrating the factory operation efficiently. It has well defined, coordinated, individual, current and consistent system of goals, adapting quickly to changes in their environment.
HMS	Holon	Emulates the stability, adaptability, flexibility and efficient use of available resources in social thoughts (biological society). The basic entity (holon) transforms, transports, stores and/or validates information and physical objects.

Table 2.12 EMS Paradigms

These enablers, (table 2.13) are shared by other manufacturing systems. Agile manufacturing defines and creates new concepts and modelling techniques to help manufacturers dynamically control, configure, adapt, and restructure manufacturing systems to cope with variations in demand patterns and production mix that result from unpredictable market changes, (Anosike *et al.*, 1999). It precedes the adoption of the other Emerging Manufacturing Systems.

Enablers		
Design Techniques	**Tools**	**Technologies**
Failure Mode Effect Analysis	Software	CAD
Taguchi method	Hardware	JIT
Quality function deployment	Networks	Intranet, Extranet, Internet
Conjoint analysis	Office tools	Groupware
Rapid prototyping	Communication tools	Product data management
Theory of inventing problem solving	Broadcast	Collaborative computing
Robust design	Wireless tools	Electronic Data Interchange

Table 2.13 Enablers of the NGMS

The basic units of these manufacturing paradigms have unique behaviours that make them worthy of consideration in a class of their own. Some of these characteristics/ properties are shown on (table 2.14) below.

Philosophy	**Characteristics**
AMS	Enablers respond to pressures, with highly capable production technology, using effective modularity and "plug and play" features.
BMS (modelon)	Modelons like cells in living organisms obtain needed inputs/ tasks and perform multiple and different operations. They propagate through a self-organising process by passage of DNA*-type information, ensuring coordination between units at different layers for harmonious performance of tasks.
FrMS (Fractal)	The entitative unit (fractal) exhibits self similarity, self organisation, self optimisation, goal orientation and dynamics/vitality. The internal dynamics of each fractal differs, but is still consistent with overall goals. Navigation and efficient information system are used for checking target areas through self organising control loops to ensure effectiveness and improvement.
HMS (Holon)	Basic entity (holon) has two opposing attributes; self-assertive expressing "wholeness" and integrative showing "partness". These attributes make it autonomous and cooperative. There is constituent information processing part and/or a physical processing part. Function is defined by fixed rules called canons and flexible strategies. The canon determines its invariant structural configuration and functional pattern, while strategies define the permissible steps and self regulates its activities.

* DNA - Deoxyribonucleic acid

Table 2.14 EMS Basic units and their characteristics

The AMS uses a parallel manufacturing approach. The manufacturing model is characterised by its effectiveness, operation and technology. It is the most popular paradigm, with wide spread application that has been extended to more than just the manufacturing components of an enterprise (Anosike *et al.*, 1999). It earns it an enabling wider participation by enterprises and niche markets. The agile approach sets the basic scenario for the successful implementation of the other emerging manufacturing paradigms. The FrMS is rated highly because of its basic unit capabilities and high ad-hocratic structure. When a new project arrives in FrMS, all the entities engage in negotiations to co-operate for the new task at hand. It is the most modern approach, and relies on individual entities' autonomy and vitality to maintain and increase system dynamics and performance. Planning and scheduling are dynamically performed through negotiation between fractals. Based on mathematical formalism, there is ease of design and specification. However, FrMS application tends to be complex, especially for implementation of movements, decision and co-ordination mechanism. The

HMS comprises holons (autonomous/ cooperative elements), people, communication network, and methods for cooperation including procedures for negotiation and resource sharing. Approaches to the implementation of the HMS look somewhat similar to the FrMS. However, a holonic structure seemingly has better operational attributes. It appears more rigid due to its structure, organisation and functional orientation, and more stable due to the statistically defined hierarchical rules, which in a sense is more like a BMS. On the other hand, the holonic functional features might look more limiting, but are compensated by self-organisation. Planning is static, but scheduling could be dynamic thus negotiation is critical for resource allocation. It uses top-down approach to define tasks and start negotiation among the holons. The BMS paradigm relies on the environment and how modelons react in order to trigger operation and cooperation under 'DNA'-type rules, for its behaviour. In comparison with the holonic and fractal paradigms, an organic planning and scheduling is hierarchical, dynamic, adaptive, flexible and evolutionary. However, managing so much information may have negative consequences if coordination and hierarchical competencies are lacking. Apart from the differences among these organisational paradigms, theory suggests that conceptually different systems can co-operate and co-exist simultaneously. Characteristics and behaviours related to different paradigms can be combined in a single system. Based on the paradigms and basic unit functions of the different manufacturing systems as presented above, the overall behaviour of these concepts are compared and contrasted looking at the mode of operation and the design perspectives in other to identify the commonalities as well as the opposite natures, purposes, etc. of the different systems.

2.7.1 Design features of EMS.

The design of the structural composition/ formal element of these manufacturing concepts exhibits strong autonomous, cooperative and sensitive tendencies while portraying the 'whole-part'/ self repeating structure in their basic units (Saad, S., and Aririguzo, J., 2007). (table 2.15). However, the difference lies in the way these views are applied in manufacturing and the adaptation of the means to their pre-conceived ends. Manufacturing entities in Bionic manufacturing system are created in a dynamic process similar to that in cell division in living organisms and through definition of DNA-type information and enzymatic actions. This aids in their swift response to changes in the environment, through performing multiple operations (Tharumarajah, A., 2003). By contrast, in Holonic system, holons are created according to the operation/ task to be performed. The autonomy in the holarchy is represented by the ability to manage the interactions, which acts as an operational closure allowing

Philosophy	Design features of EMS
BMS	Advocates autonomous, cooperative, intelligent entities (modelon). Basic structural form indicates recursive Part-whole relations. The process of creation of modelons is dynamic and straight forward, through specification of DNA-type information as in living organisms. Re-grouping is limited to initial cell division to create entity. The design of the BMS takes effect from beginning/ genesis and evolves progressively according to need of system.
FrMS	Advocates autonomous, cooperative, intelligent, recursive (self repeating) structure. The definition of fractal embodies all its features including environment, both immediate and microscopic division of functions and relations to its environment. The design of FMS is multi-dimensional. This includes the technical, human and cultural dimensions.
HMS	Stresses autonomy, cooperativeness, intelligence, part-whole relations. Holons are formed on functional decomposition of system. The essential attributes; cooperativeness, autonomy and intelligence compliment such decompositions. HMS design takes a more technically oriented approach, highlighting precision and explicit demonstration, realised from beginning.

Table 2.15 Comparison of design perspectives

interaction amongst member holons. The architectural design of the constituent elements takes place top-down, defining the holarchy first and member holons subsequently. The Fractal has a symbiotic association with its environment, enabling it to adapt in response to the environment. Reconfiguration or restructuring is flexible and can take place over time while high dynamism and vitality lends a hand in goal formation and realisation. Design of the fractal takes place in bottom-up fashion; and is multi-dimensional, capturing technical, cultural and human dimensions. It encompasses these details within it as oppose to external perception. Holonic system design adopts a more practical, predefined procedure, highlighting precision and explicit technique. Goals and tasks are realised through rules of cooperation (canons) and flexible strategies. Bionic system design specifies all system parameters from genesis, modelling functions like cell division and enzymatic operations etc. (Figures 2.14 and 2.15) show how the EMS rates in terms of resource utilization and organisation interrelation respectively.

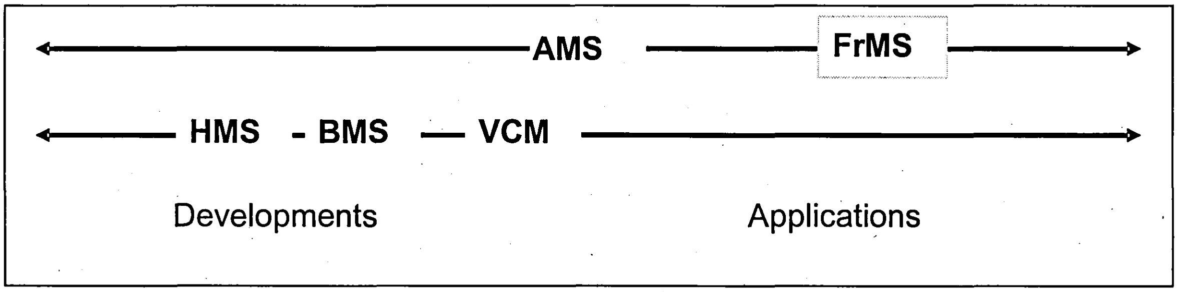

Figure 2.14 Resource Utilization level

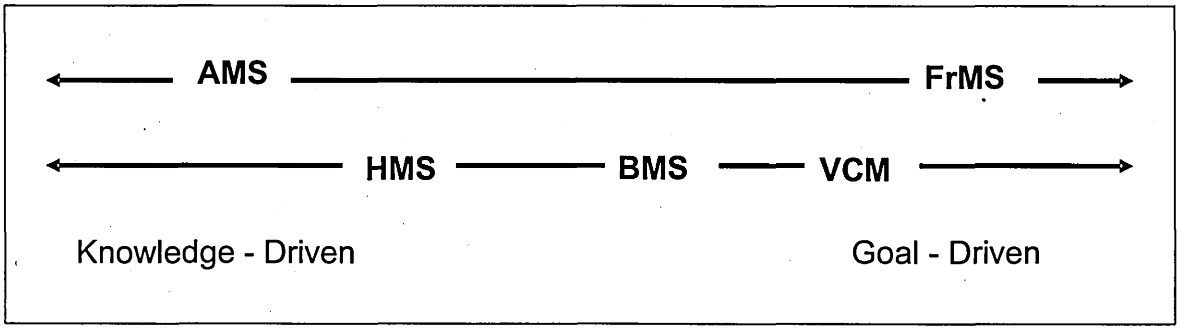

Figure 2.15 Organisation interrelationship level

2.7.2 Mode of operation of EMS.

The manner of functioning of these concepts shows strong cooperation and interdependency of units (Saad, S., and Aririguzo, J., 2007). This is obvious from both hierarchical and heterarchical perspectives. The disaggregated nature of the components of the different paradigms and absence of a centralised system of control, call for total coordination at both the inter-unit and intra-unit level of activities for harmonious operation. (Table 2.16) compares these essential properties of the different concepts. Common environment and specification of goals from genesis in Bionic manufacturing streamlines cooperation between modelons. In the hierarchical order of things, task specification is done in top-down fashion, while decision making takes place bottom-up. The Fractal and Holonic systems assume a more conventional or traditional form. The fractal system advocates global goals and goal inheritance through a top-down and bottom-up goal coordination. Holons specify goals/ tasks at higher levels and these get progressively refined by lower level holons. On inter-level cooperation, fractal navigation ensures a network of communication for goal assessment and realisation, while lateral coordination of modelons is indirect through common environment. Tasks are tackled and reacted to as they surface in Bionic manufacturing, while Fractals dynamic goal revision mechanism continuously checks target areas. Goal specification and planning is done at higher level in Holonic manufacturing and lower level holons are

Philosophy	mode of operation
BMS	High co-ordination due to functional inter-dependence among units and different ranks (hierarchy/ heterarchy of units). Promotion of unity of action through flexible forms of coordination in both vertical and lateral directions. Extensive communication and cooperative abilities of modelons. Dynamic and concurrent planning making cells react to input and output of other cells in their environment (shared fluid environment/ enzymes). Common environment promotes commonality of functional goals between 'whole-parts' and whole and parts. During operation they exhibit top down task specification and bottom up decision making.
FMS	High co-ordination and cooperation among different fractals. Promotes unity of action through flexible forms of coordination among fractals. Fractals pursue concurrent and iterative goal formation strategies. Advocates; global goals, goal formation and inheritance through coordination with a super ordinate fractal. Definitive vitality aids recording and evaluation of changes in characteristics of six levels pertaining to dimensions of work environment i.e. cultural, strategic, socio-psychological, financial, informational and technological.
HMS	Coordination among holons at different levels (hierarchical/ heterarchical) Promotes unity of action through flexible forms of coordination in both vertical and lateral direction. Holons engage in joint planning through cooperation. A form of task or goal specification is done at high level in a more consultative manner. During process planning/scheduling, coarse plans are specified and get progressively refined by lower level holons. Hierarchical coordination integrates action of lower level units rather than a command and control technique.

Table 2.16 Comparison of mode of operation

incorporated through cooperation. Regulatory mechanisms are necessary for control and coordination and to ensure harmony (Tharumarajah and Wells, 1997). These are mechanisms whereby the various activities of the component parts of a system are modified so that they contribute to the coherent functioning of the entire system. (Figure 2.16) shows how the EMS rates in terms of flow of information.

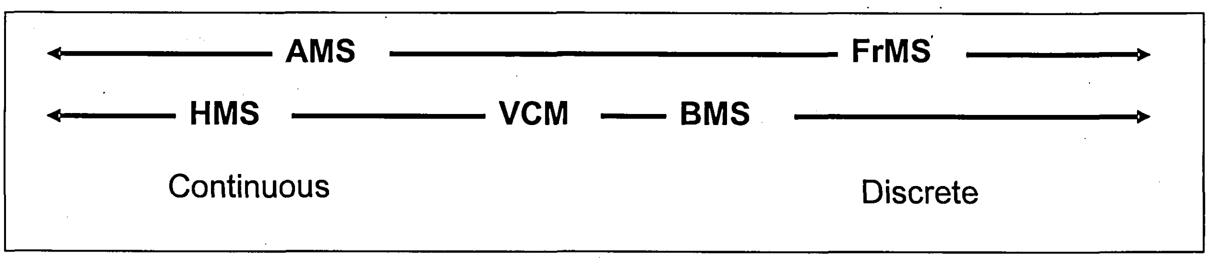

Figure 2.16 Information flow level

(Table 2.17) below shows some key characteristics of short and long term regulations. Example of short term regulations includes change to production quantities etc. Long term regulations include lowering of inventory levels, reduction in production cycle times or improving employee satisfaction (Tharumarajah, A., 2003; Tharumarajah and Wells, 1997; Ueda, *et al.*, 2000). The implementation regulation mechanism can be global, filtered through hierarchical whole-part relations and/or local.

Concept	**Type of regulation**	**Type of mechanism**		
		Global	Hierarchical	Local (entity-level)
BMS	Short-term	CNS	Enzymatic action	Enzymatic action (coordination)
	Long-term	Hormones	Hormones	Hormones, BN-type learning
FrMS	Short-term	No	Fractal navigation, JIT, Kanban	JIT, Kanban
	Long-term	No	Goal coordination	Vitality measures of environment
HMS	Short-term	No	Plan coordination	CN, Learning coordination through conflicts
	Long-term	No	Hierarchic awareness	Balance A&C through Canons and strategies

CNS: central nervous system, BN: brain neuron, CN: contract-net, A&C: autonomy & cooperation, JIT: just-in-time

Table 2.17 Comparison of regulatory mechanisms

Essentially, the regulatory mechanisms help not only to harmonise operations but also to achieve the desired short-term performance, recognise and amend entity inter-relationships, functional divisions and the organisational arrangement to avoid the long-term dysfunctional effects of an organisation.

2.7.3 Self-Organisation of EMS.

A system self-organises if it has the ability to adapt itself without an external intervention to the prevailing conditions of its environment (Whitaker, R. 1998). On the other hand, a self regulating system has the capability to actively control the course of its internal transformations, with respect to one or more parameters. A self configuring system would actively determine the arrangement of its constituent parts (Tharumarajah, A. 2003). Self-organisation is brought about through modification of individual behaviours and/or organisational structures. These could be achieved through global, hierarchical or local regulatory mechanisms. (Figure 2.17) shows how the EMS concepts and the Virtual cellular manufacturing system (VCM), self-organise for Autonomous work groups (AWGs) (Strauss and Hummel, 1995). There are four levels of progressively increasing functional responsibility of a unit, and the type of unit that results. The level of autonomy in a manager-led unit is only over the task being executed, while a self-governing unit assumes responsibility for all major functions. The sphere of influence extends beyond the immediate control of the processes depending on the position of the unit. Focussing within these four types of units, holons (holarchies) are formulated from functional decomposition of a system, concentrating on self-managing units with limited capabilities for self-design or self-governing. BMS focuses on self-management, considering the functions of modelons with multiple operations. The fractals encompass a broader spectrum of functions, covering the symbiosis with its business and operational environments (i.e. the six dimensions of a system's environment) (Sihn, W., 1997). As a result, fractals are more dynamic, with the ability to reconfigure themselves in response to environmental disturbances. (Figure 2.18) show the different EMS concepts rate in terms of information flow, their interrelationships and resource utilization.

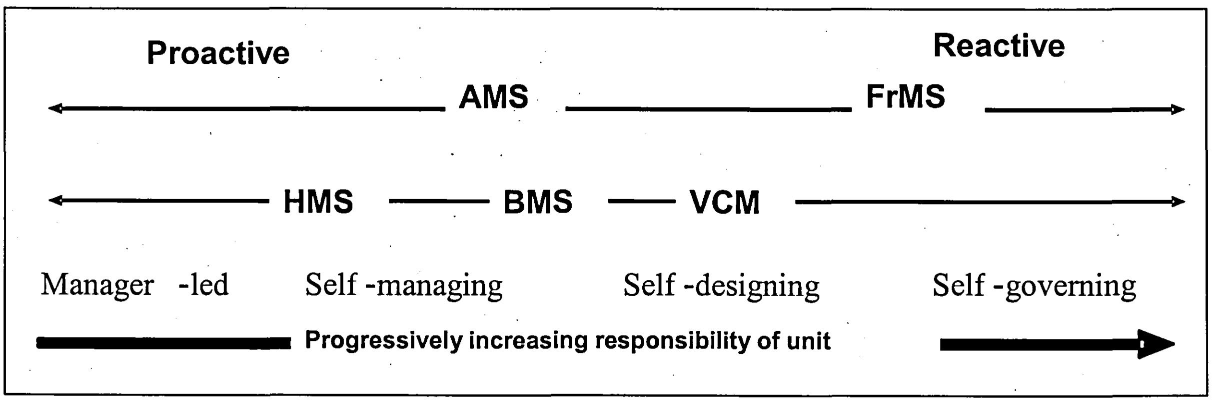

Figure 2.17 Level of autonomy of units

Considering the six dimensions of a system's environment, as shown in figure 2.18, the technology end of the spectrum addressed by the FrMS is oriented more towards applying principles of flexibility in layout and application of technologies such as Kanban and JIT

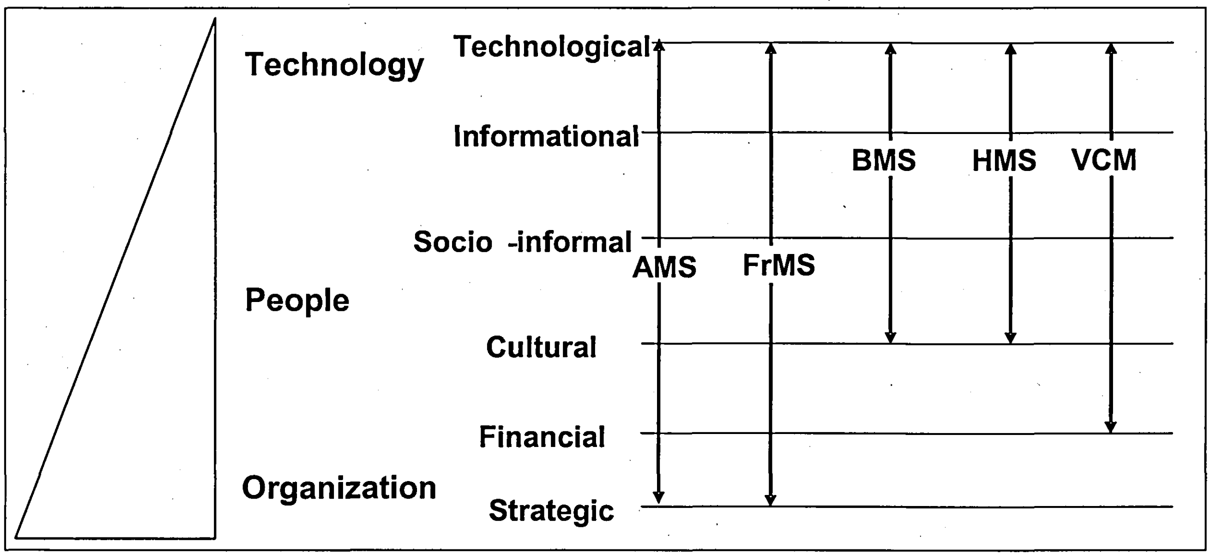

Figure 2.18 Development focus level of distributed autonomous units

(Tharumarajah, A. 2003). On the other hand, HMS and BMS in addition to such applications tend to develop technology that makes the equipment and devises themselves display autonomous behaviour in operation. These physical units are provided with intelligence and the ability to function as quasi-living things. Hence, to realise the full potential of these developments, the BMS and HMS will have to move towards the socio-technical and strategic end (Tharumarajah, A. 2003).

2.8 Research gaps and validation of research questions

The review of available relevant literature on the different EMS as made above reveal detailed developments and progress made in manufacturing system and operational management. While the underlying principles of the different paradigms are very similar according to the assessments conducted by Tharumarajah *et al.* (1996, 1998), Kadar *et al.* (1998), Sousa *et al.* (1999) and Ryu and Jung (2003), these proposals have been based within the context of selected narrow areas of basic shop floor operations and management and fall drastically short of taking into account the wider supply chain management issues. It's been proven that supply chain management is critical to the success of manufacturing organisations, especially given the landscape of the 21st century manufacturing. So enterprises have to learn to look beyond their own immediate four walls (Li *et al.* 2002; Michael, H., 2003). Individually or while considered in isolation, the EMS paradigms have some of the capabilities emphasized by Ryu and Jung (2003) as pre-requisites of the 21st century manufacturing system (i.e. intelligent, flexible, adaptable, autonomous, and distributed system with independent function modules). Examples of these applicable attributes include; the responsiveness of biological scheduling and control (Vaario and Ueda 1997; Vaario and Ueda 1998a), organisations and scheduling in holonic manufacturing (Bongaerts *et al.* 1997b, Sousa and Ramos 1998), flexibility of resource elements and representation of machine capabilities and product requirements in responsive manufacturing (Gindy *et al.* 1996, Saad and Gindy 1998) and agile manufacturing systems (He *et al.* 2001). The FrMS is noteworthy for the efficiency of its shop-floor configuration (fractal layouts) (Venkatadri *et al.* 1997, Montreuil *et al.* 1999). Fractal cells are also multi-functional, flexible and scalable (reconfigurable). They have the ability to perceive and adapt to changes in their environment and to uncertainties, which attributes are pertinent as mentioned earlier (Ryu and Jung 2003) and therefore deserves further attention and research. Moreover, the fractal manufacturing partnership (FMP) (Noori *et al.* 2000) lends itself wholly to the imperative subject of supply chain management implementation, because it brings suppliers closer to the OEMs in a new revolutionized collaboration as we will see in chapter seven. Hence, bridging the supply chain gap by applying the fractal paradigm and architecture (Saad, S., and Aririguzo, J., 2007a) is directly relevant to the research questions in this research, because it forms the bedrock for the development of lean and agile ('leagile') capability and more importantly because businesses depend on their supply chains to provide them with what they need to survive and thrive in the 21st century volatile global market (Michael, H., 2003) as we will see in chapter six.

2.9 Conclusion

Basic review of relevant literature relating to manufacturing systems and operational management was made in this chapter. Initially, the progression of manufacturing was traced to the 21st century. This is followed by the challenges of manufacturing owing to advancements in technology coming into the new millennium. Then traditional manufacturing method was bared, highlighting why it is not standing up to the new manufacturing challenges. The EMS are then compared and contrasted highlighting research gaps, justifying why more research is needed on the FrMS and validating the research questions asked and listed in chapter one.

Chapter Three

3.0 Research Methodology

In this chapter, the topics of research methodology, tools and research techniques were presented. Initially, the chapter devices a methodology for the research project, then it deploy this in answering the research questions. It then presents the various mathematical tools, techniques and methods used in achieving the set targets. It also presents a clear and concise overview of basic principles and available computing techniques for carrying out enterprise modelling and integration.

3.1 General Perspective

The conceptual ideas of the emerging manufacturing systems are very hazy, with no elaborate insight yet, or in-depth plan towards their industrial implementation. This research looks and concentrates particularly on the fractal manufacturing system as a novel approach in forming enterprise/ supplier partnerships and supplier networks. The distinctions between the conventional supply chain, supply network and total fractal supply network are obvious and are instantly identifiable. In figure 3.1, while the conventional supply chain pertains to a linear relationship as marked by asterisks, the internal supply network is a more complicated, networked/interconnected relationship and consists of first and second tier suppliers. The fractal supply network on the other hand consists of fractals with their inherent,

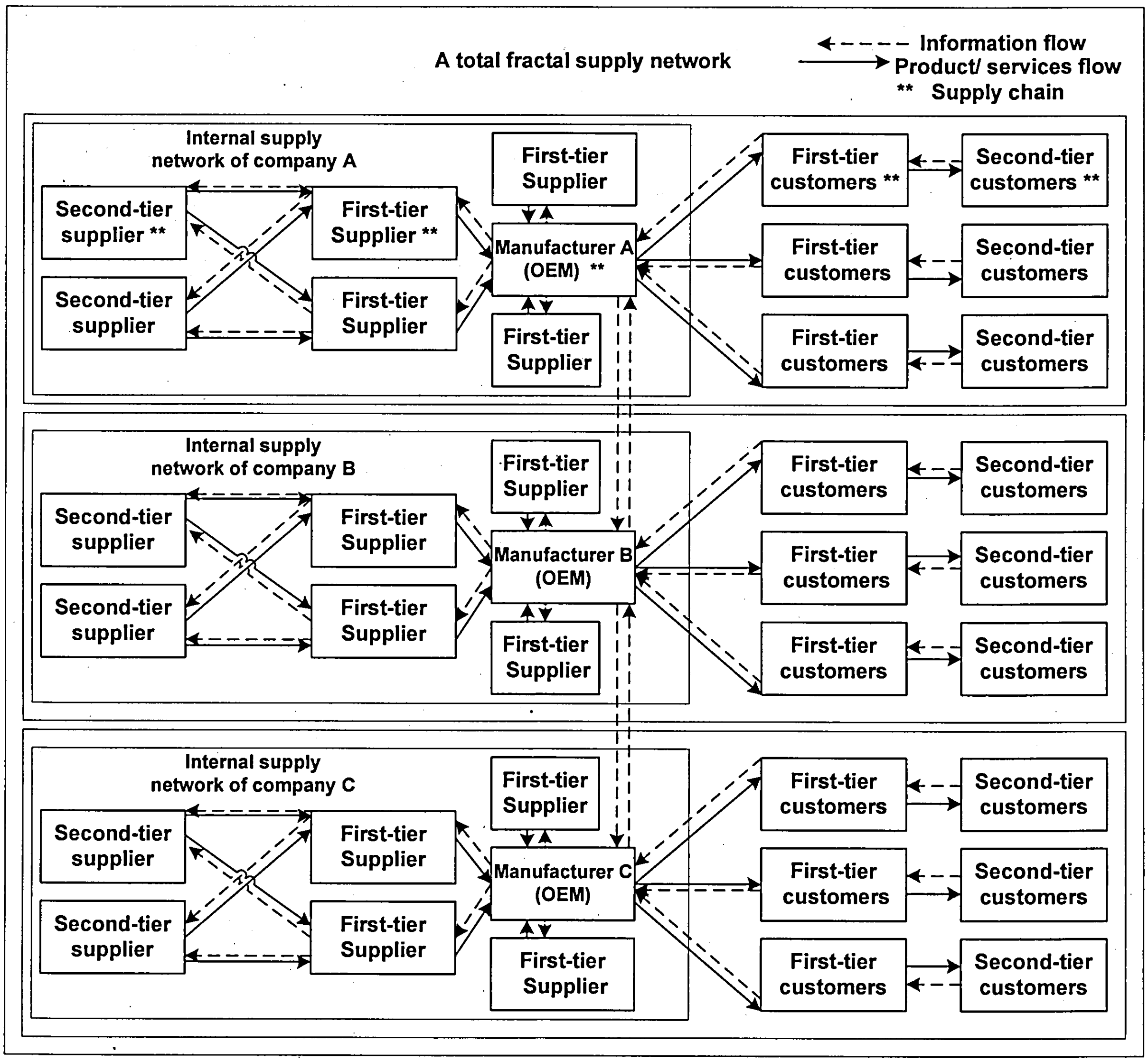

Figure 3.1 The total fractal supply network

congenital characteristics - self similarity, self organisation, goal orientation, dynamics and vitality etc. The fractal manufacturing partnership also forms a close alliance with key suppliers who share the manufacturers' facility and become assemblers. In figure 3.1, the manufacturer goes into collaboration with first-tier suppliers who source, design and make components in collaboration with second-tier suppliers. On completion of the production process, the manufacturer supplies the product to first-tier customers (dealership), who in turn supply to the end customer (second-tier customer). The fractal manufacturing system solution deploys an entirely new holistic and decentralized perspective in forming leaner core business units supported by supplier networks. This is used to develop 'leagile' networked enterprises.

This study focuses on investigating and contributing to insights into the Fractal manufacturing system and Fractal Manufacturing Partnership (FMP). This new collaboration between OEM and key suppliers, where suppliers become assemblers of their components is modelled, simulated and tested by a comprehensive computational representation. The study involves formulating and analyzing the developed conceptual system since the fractal system is still in the conceptual stages without clear implementation strategies as at yet. The fractal architecture proposed in this research (figure 3.2) develops, implements and establishes an inter-related set of components that form the basic structural backdrop especially in the management of a total supply network (Davis, T., 1993; Barnes, R.E., 2007). First there is internal design of the fractal enterprise. Then development of the broader fractal supply network, integrating the lean and agile attributes to maximize logistical network capabilities. A revolutionary alliance (FMP) is modelled, bringing OEMs and suppliers together and formulating a framework for selecting suppliers prior to the FMP.

The experiments and testing in this study are based on generation and evaluation of hypothetical quantitative data. There is comprehensive validation of these data and confidence intervals are fitted to ensure reliable results. When theory is applied to the process it attempts to describe, it is called deduction (Gilbert 1979). A situation where theory is generated from observation of the process known as induction, is also popular. This research will involve both deduction and induction processes.

The study is broken up into sequential integral elements and milestones which are investigated individually and the successful result from one lunches the study unto the next. Initially a new genetic algorithm approach is applied in modelling the fractal shop floor. The research then proceeds to looking at broader subject of fractal manufacturing partnership, creating criteria used in selecting quality suppliers prior to forming and harmonising the partnership between manufacturers and these key suppliers. Ultimately, this coherent, synergic alliance promotes an integration of lean and agile manufacturing system solution downstream in the fractal supply network.

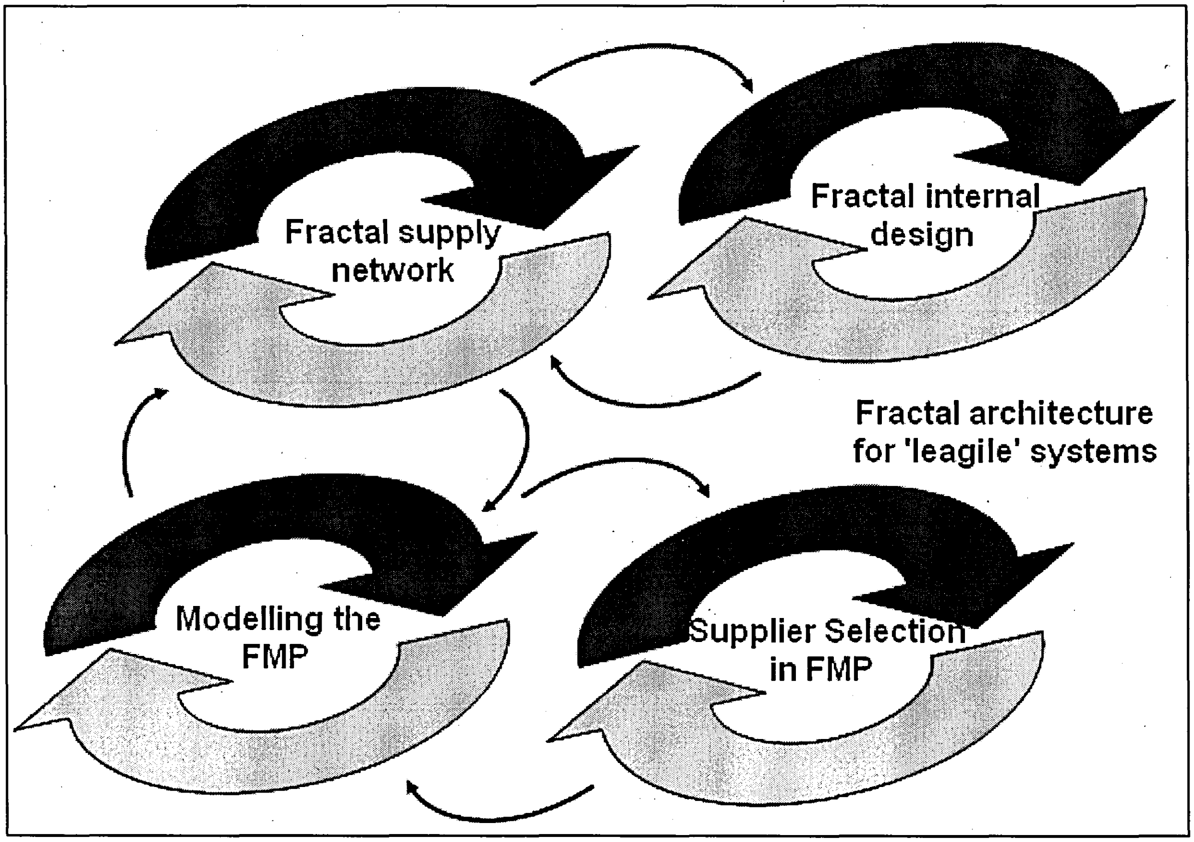

Figure 3.2 The proposed fractal architecture

3.1.1 Some basic definitions

Throughout this chapter and elsewhere, a number of commonly used nomenclature and phrases are used frequently and might need to be defined before-hand. These include the following;

- **System:** A system is an aggregation or assemblage of things so combined by nature or man as to form an integral and complex whole (Encyclopaedia Americana). Mathematical systems theory studies the interaction and behaviour of this assemblage when subjected to certain conditions or inputs.

- **Modelling process:** This is the set of activities to be followed for creating one more models of something (defined by its universe of discourse) for the purpose of representation, communication, analysis, design or synthesis, decision-making, or control.

- **Model:** A model is a useful representation of some subject. It is a formal abstraction of a reality expressed in terms of some formalism (or language) defined by modelling constructs for the purpose of the user.

- **Modelling framework:** A modelling framework is a collection of modelling principles, methods, or tools relevant for a given domain of application.

- **Enterprise:** An enterprise is a socio-economic organisation created to produce products or to procure services and to make profit.

- **Business process:** A business process is a sequence (or partially ordered set) of enterprise activities, execution of which is triggered by some event and will result in some observable or quantifiable end result.

- **Modelling construct:** A modelling construct is a primitive of a modelling language, the syntax and semantics of which must be precisely defined. Formal description techniques are defined by constructs having a good syntax and semantics. Diagramming languages usually have an expressive syntax but a poor semantic definition of their symbols.

- **Reference model:** A reference model is a partial model which can be used as a basis for particular model developments or for evaluation of particular models. Often, a reference model is used for comparing something to a reference. It can also be used as a reference to derive particular models from predefined models.

- **Architecture:** An architecture is a finite set of interrelated components put together to form a consistent whole defined by its functionality.

- **Reference architecture:** A reference architecture for a given domain is a generic architecture from which other architectures can be compared or derived.

- **System life cycle:** A system life cycle depicts the sequence of phases the system goes through over its entire existence.

3.2 Research Process

Analysis of problems in the real world often involves synthesis of these problems and/or developing theories to explain them (brogan 1991). Understanding a particular phenomenon might involve mathematical modelling by means of a function or an equation of the phenomenon (Giordano *et al.* 2003). Such mathematical models serve as an idealization of the problem in hand. System models can be developed by two distinct methods; Analytic modelling - which consists of systematic application of basic physical laws to system components and the interconnection of these components, and experimental modelling also called modelling by synthesis which is a selection of mathematical relationships which seem to fit observed input-output data (Brogan 1991). A model language is more or less formal and is made of constructs (Vernadat 1996). An example of formal description technique is the LOTOS language, while a semi-formal language is the IDEF notations. The process of research starts in one of two forms - deductive or inductive procedures (Gilbert 1979; Saunders *et al.*, 2003; Gill and Johnson, 1991). Deduction (also called testing theory) is a technique for application of theory, while induction (which is also called building theory) is a means of generating theory. This research employs predominantly deductive method and some elements of inductive approach. The theory or hypothesis will be developed and tested appropriately. This type of research is popular in the natural sciences where the laws provide the basis for the explanation and predict their occurrence. On the contrary, in inductive approach the theory is developed by analysing data collected and/or the technique is gotten as an application of the theory developed. This is popular among the social sciences. However, (Gilbert 1979 and Saunders *et al.*, 2003) proposes that a scientific model is incomplete without both procedures and that it is difficult to separate the two in practise. It is also possible to choose to move from observation to the generation of theory (inductive research) or to start with theory and tests (deductive research). The characteristics of deductive and inductive approaches are classified as qualitative research and quantitative research respectively and dealt in detail by (Locke 1998 and Taylor *et al.* 1984). They also highlighted the impacts of both methods in solving a research problem (Table 3.1).

Deductive approach	Inductive approach
Use of controls, physical or statistical so as to allow the testing of hypothesis.	Commitment to research in everyday settings, to allow access to, and minimize reactivity among the subjects of the research.
Generation and use of quantitative data.	Generation and use of qualitative data.
Explanation by analysis of causal relationships and explanation by covering laws.	Explanation of subjective meaning systems and explanation by understanding.
Highly structured research methodology.	Minimally structured research methodology.
Strategies include; experiments and surveys	Strategies include; survey, grounded theory, case study, ethnography, action research
Deals with scientific principles	Deals with human attached events

Table 3.1 Characteristics of Deduction and Induction research processes

3.2.1 Sequence of research events and key milestones

Extensive investigation of the fractal manufacturing system as one of the most promising of the emerging manufacturing systems, with many conceptual advantages (Ryu and Jung, 2003) for tackling the 21st century manufacturing challenges and concerns is the purpose of this study. (Figure 3.3) shows a sequence of events put together towards that end and aimed at addressing the research questions. For a start there is general review of manufacturing which aids determination of appropriate title for the study, aims and key objectives, benefits and innovation from which the research questions are extracted.

Comprehensive literature review follows, tracing the historic development and progression of manufacturing right on up to the 21st century, and juxtaposing the emerging manufacturing systems to compare and contrast their strength and weaknesses. Then an adequate methodology is determined for the research. The fractal concept, its origin and characteristic features are dealt with next. This is followed by the modelling and simulation of the fractal manufacturing partnership (FMP). The criteria are formulated for selecting suppliers prior to going into the FMP. And then the subject of fractal supply network, where the lean and agile concepts are integrated within the fractal environment is looked at. Then the research is concluded and a few recommendations are made.

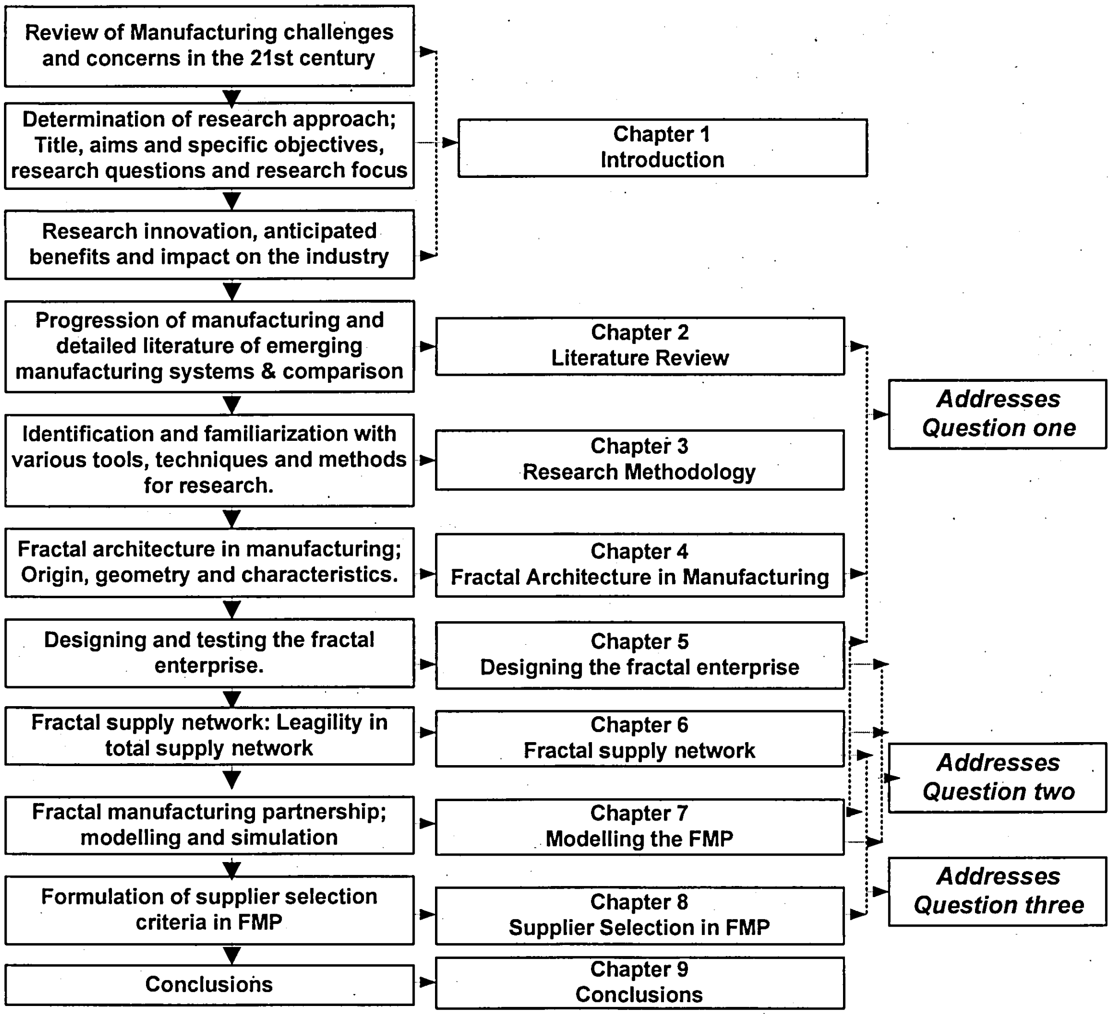

Figure 3.3 Sequence of research events and how they address the research questions

3.3 Research tools, techniques and methods deployed

In this research project, a comprehensive computational representation of the Fractal enterprise and the FMP is made using modeling and simulation. This aids in evaluating its performance in dynamic conditions. The structure, resources, behavior, strategic objective, values and constraints is captured through enterprise design, analysis, and operation. Understanding of the nature and working of FMP before conducting statistical experiments is also crucial in the final results of the modeling. The output data of the simulation is used to identify system bottlenecks and to generate alternative states that may provide the desired performance improvements for the system.

3.3.1 Mathematical modelling

To understand and control complex systems, some kind of quantitative mathematical models of these systems must be obtained (Dorf and Bishop 2005). Quantitative mathematical models of physical systems are particularly applicable in the design and analysis of control systems. It is therefore necessary to analyse the relationship between the system variables and to obtain a mathematical model.

Mathematical modelling is also called a logical model. It is a structural and quantitative approximation of the real system (Kelton *et al.* 2004). It can be captured through a computer program that is run to highlight and address questions about the system models behaviour. Most times the hypothesis in mathematical models comes from laws of physics, chemistry, gas dynamics and conservation of energy and momentum (Kapur 1998; Brogan 1991; Giordano *et al.* 2003). Then these are translated mathematically using traditional mathematical tools expressed in terms of differential equations, integrals, integro-differentials or linear programming etc. which is evaluated and solved numerically for instance through taking partial derivatives of it with respect to controllable input parameters, analyzed or simulated. Most of the time these provide a simple closed-form formular or an algorithm to generate numerical answers. A valid logical model representation of a target system can throw some light on ways of dealing and analysing the systems behaviour. Furthermore, if the system under consideration is dynamic in nature, the descriptive equations are usually differential equations (Dorf and Bishop 2005). Two mathematical techniques lend themselves to the course of this project. These are Genetic Algorithm (GA), and Analytic Hierarchy Process (AHP). Genetic Algorithm is a class of evolutionary algorithm that is inspired by evolutionary biology (Kamrani *et al.*, 2003). It is a search technique used to find approximate solutions in optimization problems. The GA approach is a powerful and broadly applicable stochastic technique. It continuously iterates and optimizes the design of the fractal layout and flow assignment according to the performance of these parameters. Analytic Hierarchy Process (Saaty 1980; Saaty and Vargas 1981; Saaty and Vargas 2000) is a structured technique for solving complex multiple criteria problems involving comparison of decision elements which are difficult to quantify. It converts evaluations into numerical values that can be processed and compared over the range of the problem. The AHP approach will be applied in the formulation of criterion for supplier selection for the fractal manufacturing partnership.

3.3.2 Modelling and simulation tools

Computer simulation normally mimics a real system features by numerical evaluation using appropriate software designed for that particular system (Kelton *et al.*, 1998). Models of the fractal system, including layout and supply chain are studied using computer simulations. Programming language is used to represent this simulation models on computers.

3.3.2.1 Traditional general-purpose programming languages

High level programming language, such as FORTRAN, Pascal, Visual Basic and C are not very popular these days owing to complexity and high requirement of programming skills. They are still employed by many modellers seeking flexibility, customizability, low cost, efficiency in execution and applicability towards many areas. However, program development is slow and prone to logical errors. C++ programming language is used to write codes for formulation of fractal layouts and the supplier selection criteria.

3.3.2.2 Special-purpose programming languages

Special-purpose simulation languages e.g. GPSS, Simscript, SLAM and SIMAN provide a much user-friendly framework that suits many modellers (Kelton *et al.*, 2004). The level of flexibility is compromised but it offers a much faster alternative for model development. Arena packages (Kelton *et al.*, 2004) integrates the ease of high-level simulators with flexibility of simulation languages and general purpose procedural languages. It is also discrete-event oriented in nature, making it highly suitable for manufacturing applications.

It is designed to describe, model and analyze an existing or proposed application accurately and gives maximum flexibility to systems. It integrates all simulation related functions; animations, input data analysis, model verification, and output analysis into a single simulation modeling environment (Kelton *et al.* 1998). Its flexible flowcharting objects will be used in this project to capture the essence of the FMP system being considered and compare different competing manufacturing scenarios, so as to select one that best meets the objectives. Visual Basic for applications (VBA) is a technology used to write custom program codes that argument Arena model logic. VBA is embedded directly in Arena to enable writing codes (via the visual basic editor) that automate other applications such as excel, auto cad or Visio. VBA code will be used in this project to automate Arena, such as to get values of a simulation output statistics, change values of module Operands or add animation variables (Kelton *et al.*, 2004). Opt quest for Arena is an optimization tool and will be used to analyze the results of the simulation runs. It includes sampling techniques and advanced error control to find better answers faster (Rathmell *et al.* 2002). This package combines the metaheuristics of Tabu search, neural networks, and scatter search into a single, composite search algorithm to provide maximum efficiency in identifying new scenarios (Kelton *et al.*, 2004; Kelton *et al.* 1998). Finally the Arena Output analyzer will be used in fitting confidence intervals on expected output performance measures, and statistical comparison of alternatives (Sweet and Grace-Martin 2003).

These applications will be used in;

- Building and developing a virtual scenario for the proposed fractal architecture and FMP.
- Finding the best fit and balance for the enterprise/ supplier partnership to ensure a harmonious collaboration and high level of responsiveness.
- Calculating the best mix of resource capacities to maximise throughput in the integration of lean production/ agile network capabilities.
- Finding the optimal balance for the system in a volatile environment while meeting the conceptual benefits of the FMP.
- Finding the minimum costs/ maximum profits using this system in a volatile environment while keeping customer service goals level in check.

An organized set of procedures and guidelines are used for specifying the structural and quantitative parameters and relationship between the factors affecting the output performances. These factors are varied systematically with a view to finding and identifying the optimal conditions that most influence the results. Important variables are identified and investigated. These are defined, measured and controlled during the simulation exercises with a view to tracking their level of variation.

MATLAB is a high-level computer language for scientific computing and data visualization built around an interactive programming environment (Kiusalaas 2005; The Math Works 1996). It integrates computing, visualization and programming in one user-friendly environment. Its interactive oriented nature makes it easy for programs to be tested and debugged quickly. MATLAB programs can be developed within a short time though it does not produce stand-alone applications. It is typically used for maths and computing, algorithm development, modeling, simulation and prototyping, data analysis, exploration and visualization, scientific and engineering graphics, application development, including graphic user interface building (The Math Works 1996). In the course of this research, MATLAB will be used to develop, implement, customize and create a user-friendly interface for our fractal layout and supplier selection criterion.

Chapter Four

4.0 Fractal Architecture in Manufacturing

In this chapter, an extensive investigation of the subject of Fractal and the fractal manufacturing system is made. Initially, the fractal concept is described, tracing its origin, geometry and characteristic features including the fractal specific characteristics. The chapter progresses with presentation of the Basic Fractal Unit (BFU) which is the main component of the fractal system, the functional modules, and the subject of fractal manufacturing layout. The chapter ends with the fractal manufacturing system, a clear and concise distinction between the traditional manufacturing system and the fractal system. Then a critique of the traditional system is made to show why it has not seen the light of day in the 21st century.

4.1 The concept of Fractals

The subject of fractals deals with random, irregular geometric dimensions that have non-integer values, and the problem of describing/ analysing geometric objects in multi-dimensional spaces (Mandelbrot 1977 and 1982 and Fleischmann *et al.* 1989). The concept was developed by Benoit Mandelbrot in 1977, and since then has pervaded almost every branch of science. Mandelbrot studied the irregular and fragmented patterns of nature and was intrigued by the high degree of complexity they exhibited (Mandelbrot 1977).

Benoit Mandelbrot (1977&1982) describes these irregularly shaped objects that could not be explained by classical Euclidean geometry. The term fractal is coined out of the Latin 'fractus' meaning fragmented or broken/ fractured. Fractal shapes include mountain ranges, coastlines, wild ferns, cloud formations, snowflakes, fungal growth, nerve fibres and electrical discharge patterns, to mention just a few. The most popular kind of fractals is seen in the geometric model of Brownian motion. They are generated through repeated mathematical processes. He defined a fractal as a geometric object that satisfies a specific technical condition, namely having a Hausdorff dimension strictly greater than its topological dimension (Fleischmann *et al.* 1989). Their patterns are repeated at every scale to produce irregular shapes or forms that can not be explained by classical geometry (figure 4.1). Through repeated applications of very simple rules of calculation, these self similar structures inherently have high degrees of organisation. Mandelbrot's fractal explanation was based on self similarity and fractal dimension. More recently, (Shin *et al.* 2008a) regards fractal as a set that has the following properties; a fine structure with detail on arbitrarily small scale, too irregular to be described in traditional geometric language- both logically and globally, self similar -approximately or stochastically, having Hausdorff dimension, namely fractal dimension, greater than its topological dimension, and defined in a simple way, that is recursively.

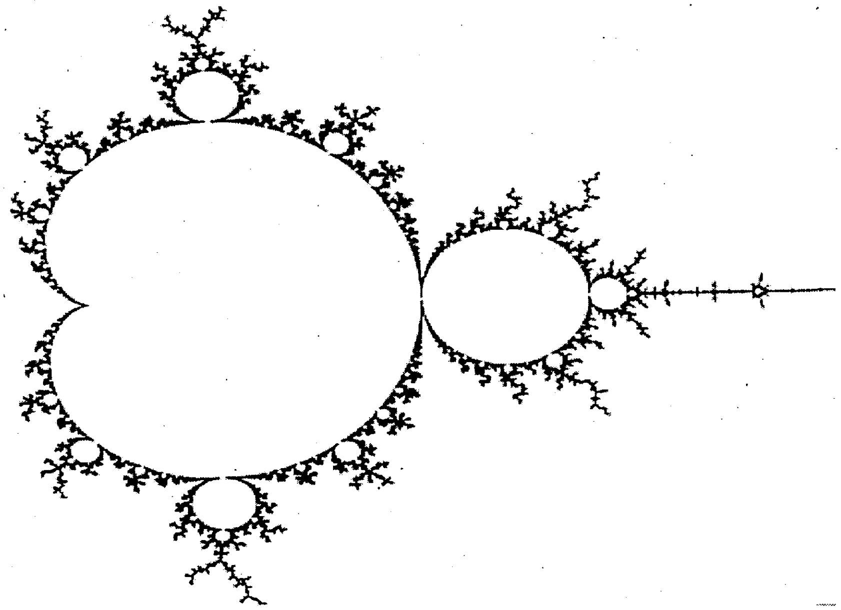

Figure 4.1 The Mandelbrot set (From Warnecke 1993)

In mathematics, (Shin *et al.* 2008a) fractal describes natural geometric pattern whose form and configuration remain invariable when resolution into its structure is increased (Hastings and Sugihara, 1993). This behaviour produces a 'pattern within patter' formation. The fractal concept reflects in every aspect of the fractal manufacturing idea. The natural fractal behaviour embodies very distinct and important characteristics. These include self-similarity, scale invariance and self-affinity.

4.1.1 Scale invariance

Scale invariance is an example of self-similarity where at any magnification there is a smaller piece of the object that is similar to the whole. Self-similarity of natural fractals means that the object is exactly or approximately similar to part of the original object. They can be decomposed into smaller copies of themselves, meaning that the structure of the whole is contained in its parts. In mathematics, it describes objects that are exactly or approximately similar to a part of themselves - the whole has the same shape as one or more of the parts. Self similar forms in nature include mountain ranges, ferns etc. Their parts show the same statistical properties at any magnification.

Scale invariance in natural forms explains the feature of objects that remain unchanged under magnification or contraction, i.e. as scale is increased or diminished over a fairly wide range of scales, (Figure 4.2). This feature is exhibited by an object, when it does not change if its length scales or energy scales are multiplied by a common factor. The assembly of fractals from their natural building blocks (smaller self similar fractals) appear to capture essential aspects of the growth and breaking rules of nature (Hastings and Sugihara, 1993). Dimensionless quantities in general - that is quantities that do not have a physical unit are scale invariant.

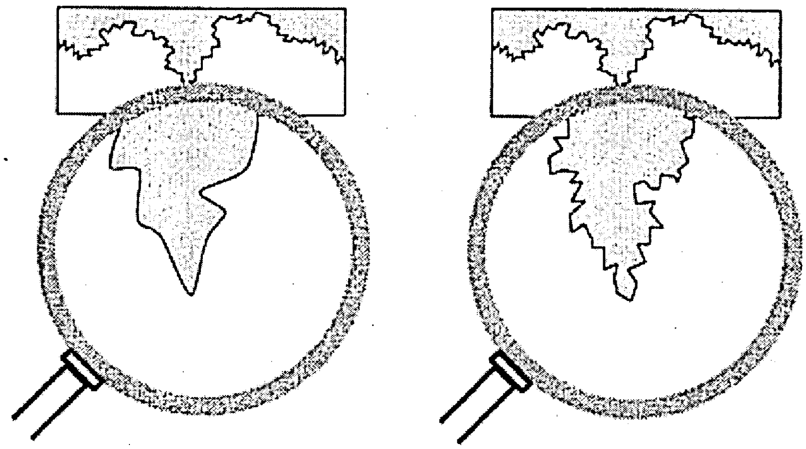

Figure 4.2 Scale-invariant behaviour (adapted from Warnecke 1993)

A ready example of scale invariance is the side of a Koch snowflake that is both symmetric and not affected by scale. The beauty of fractal images and their applications especially in chaos theory has aroused so much interest and research. It has made them very familiar. They are simply seen everywhere. (Mandelbrot 1977) thinks that natural patterns may display underlying simplicity through scale-invariance despite extremely complex appearances. "Fractals provide a workable middle ground between the excessive geometric order of Euclid and the geometric chaos of roughness and fragmentation" (Benoit Mandelbrot 1982). The challenge then is to investigate the morphology of these formless, almost amorphous patterns and ultimately bring out order from these chaotic disorders. Fractal applications are found in fractal graphics, fractal dimensions for complexity quantifications and in fractal image compressions in image processing (Flook, 1996). This was achieved after the discovery of fractal transform in 1987 by Michael Barnsley. These can detect fractal codes in real world images and natural formations. It has led to practical applications such as fractal image compression used widely in multi-media computer applications. The fractal concept has also been adopted as a design principle in such diverse fields as statistical mechanics, computer graphics, and system designs, which are based on the idea that a rather simple iterative process may produce highly complex patterns (Shin *et al.* 2008 & 2008a).

4.1.2 Self-affinity

(Mandelbrot 1992) also found a weaker scale-invariant property of fractals, for the graph of 'Brownian motion', which is called 'self-affinity'. Self-affinity refers to a fractal whose pieces are scaled by different amounts in the x- and y-directions. This means that in order to appreciate the self similarity of these fractal objects, they have to be rescaled using an anisotropic transformation. Anisotropic transformation is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. It can be defined as a difference in a physical property (absorbance, refractive index, density, etc.) for some material when measured along different axes. An example of this behavior is the light coming through a polarizing lens. However, (Hastings *et al.* 1993) think that natural patterns appear statistically scale-invariant. They are unchanged under magnification or contraction, at least over a fairly wide range of scales. Fractals are scale invariant, and random fractals are statistically scale invariant. (Lauwerier, 1991) opines that the idea of self-affinity exhibited by fractals is based on chance. He calls the fractal figure 'the motif' and is rather puzzled by the fact that it repeats itself on an ever diminishing scale. This recurrent thematic element manifests conspicuously from a panoramic perspective. Methods based on chance are formally called stochastic methods or more casually Monte Carlo methods. The essential feature of chaos or chance in this respect is the unpredictability of the system in question. Though chaos is different from random, in that random systems contain uncertainty and as a result output can not be predicted exactly. In chaos, the problem is deterministic and there is little uncertainty in the system model (Slotine *et al.* 1991). When chance is imitated using the computer, it is know as deterministic chaos. (Fleischmann *et al.* 1989) sees the notion of fractals and their characteristic behavior as the study of order in geometric chaos. They studied them as diverse rough patterns as is present in noise, turbulence and geographical features. (Hastings *et al.* 1993) went further to say that indeed the assembly of fractals from their natural building blocks (small self similar fractals) appears to capture some essential aspects of the growth and breaking rules of nature.

4.2 Organisational structure in the fractal company

Warnecke (Warnecke 1993) ingeniously applied the concept of fractal to manufacturing early in the 1990s. He applied the self-similar property into corporate structure of company and presented a new organisational concept. The fractal architecture he formulated represents a hierarchical structure built from elements of a single basic design. This self-similar agent autonomously cooperates and negotiates with others to coordinate its tasks. Hopefully, by mimicking nature's algorithm in the natural fractals, and guessing its laws of order, the same can be applied to chaotic manufacturing circumstances. In their work, (Sihn and Von 1997) opined that the organisational fractal company is characterised by an open and dynamic system consisting of quick and self similar feedback loops, enabling them to adapt to changes in their environment.

4.2.1 Assembly within Assembly

The fractal is an independent acting corporate entity whose goals and performance can be described precisely (Warnecke 1993). The idea of a 'pattern within a pattern' is applicable to organisational structuring of distributed manufacturing systems (Shin *et al.*, 2008). (Strauss and Hummel 1995) in their work on industrial engineering, says that a fractal is a partial system of an enterprise which offers opportunities for entrepreneurship to all employers, and it has a relation with other fractal units as a service centre. Each fractal is a customer as well as a supplier within the enterprise, and plays the role of an individual service centre within other service centre, i.e. 'a design within design' or 'assembly within assembly'. Each business unit of the factory acts as an autonomous factory which is integrated within a communication network (Sihn and Von 1999). Every fractal unit has or is inherently equipped with the fractal specific characteristics. This include; self-similarity, self-organisation, self optimization, goal orientation and dynamics (Warnecke 1993). These are congenital attributes of fractals.

4.2.2 Decentralized hierarchical structure

The fractal structure is characterized by constant evolution with respect to its partners and environment (Tharumarajah *et al.* 1996). The administrative functions in the fractal company are distributed over a less concentrated area. Each hierarchical structure is subject to a constant dynamical process of change, making them more suitable and adaptable to a turbulent environment. This structure is also more flexible because it is susceptible to modification or adaptation and more responsive to change. Every fractal has the same functional modules which are well-defined interfaces to the other components. In terms of job processing, there are no specified objectives, because this is carried out through the goal-formation process. Component relationship exists, whereby there is a coordinative higher fractal and an active lower fractal. Tirpak and his colleagues (Tirpak *et al.* 1992) think that the fractal model manages the structural complexity and coordination of a flexible manufacturing system, FMS by maximizing local functionality and minimizing global control. In particular, the structure and functionality of the Basic Fractal Unit (BFU), offers the opportunity to maximally localize functionality and control at each level of the FMS hierarchy in a uniform and organic fashion that methodically accommodates hierarchies of essentially unlimited extent.

4.3 Fractal Specific Characteristics

Fractals have peculiar characteristic behaviours. These are congenital attributes inherently present in them which summarize the essential feature of the fractal factory. This makes them an independently acting corporate agents whose goals and performance can be described precisely (Warnecke 1993). The fractal factory is not immediately discernible from an external perspective, but the potentials lie in the internal values and corporate culture.

4.3.1 Self-similarity

This property depicts the formation of sub-structure similar to an overall structure. A small detail repeats elements of the overall formation. It builds patters within patterns, in a multi-dimensional appearance. Each fractal is itself a small fractal factory. However, it refers not only to the structural characteristic of organisational design but also describes the behaviour of performing a task, as well as the formulation and pursuance of goals (Warnecke 1993). The fractal factory has several work cells, each containing one or more sub-cells. A fractal must be itself a little 'fractal factory'. In the resulting hierarchical structure, a fractal can represent an entire manufacturing system at the highest level or a single machine at the lowest level. What this implies is that an individual must perform his task as comprehensively as the company. There can be different ways of solving the same problem in the manufacturing environment. Even though there can be components with shared goals in the system, conditions or situations of the system environment may be different from others. Fractals with different internal structure, due to several different approaches to problem resolution, chasing same goals produce the same output with same input as depicted in (Figure 4.3). Self-similarity should be regarded in view of a functional structure, not of the structure of the physical equipment (Ryu and Jung 2003).

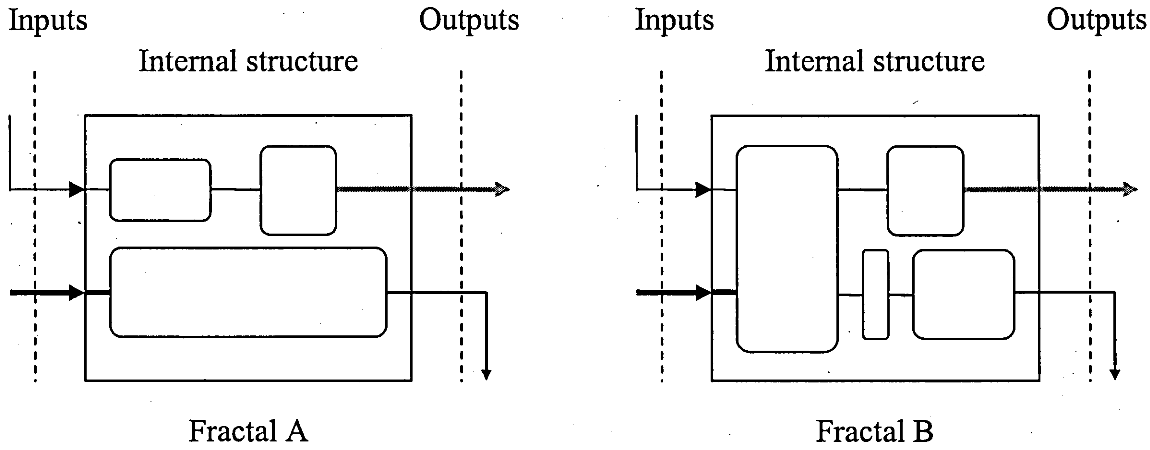

Figure 4.3 Self-similar fractals with different internal structure (From Warnecke 1993)

Fractals can also exist independently on their own, not necessarily remaining in the factory, while still networked and interconnected to other fractals, and having access to all support mechanisms, information and resources like every other fractal. This creates a network of interconnected companies. All services are performed in their entirety in the interest of holistic task completion and as independently as possible from other fractals. The characteristic of self-similarity also refers to the structuring behaviour of organisational design (Warnecke 1993). However, it is not enough to build 'factories within a factory'. (Warnecke and Huser 1995) argue that organisational units should be all pulling in the same direction in order to coordinate their integrated structure. Thus, self-similarity is also introduced into the corporate goals of the company and its fractals. The similarity does not only refer to the internal organisation of the fractals, but also to the goal system (Shin *et al.*, 2008). Similarity of goals means conformity of objectives in each organisational unit (Sihn and Briel, 1997).

4.3.2 Self-organization

This attribute aids fractals in handling changes, and in process dynamic restructuring (Kadar *et al.* 1997). Its role in task execution is also significant. Self-organization affects both the operative and the tactical and strategic levels (Warnecke 1993). The notion of constant and continuous improvement is harnessed and takes direct and immediate implementation. Self-organisation also implies degrees of freedom for the fractals in the organisational structure as well as for the handling of the processes to execute their tasks.

4.3.2.1 Self-Optimization

The theoretical self-organisation is also called self-optimization (Ryu and Jung 2003). The operative self-organisation means the application of suitable methods for controlling processes and optimizing the composition of fractals in the system. For example, the performance of the entire system decreases if the work load of fractals is not balanced. Fractal units are able to select their own methods suitable for problem solving and process improvement, and thus different fractals use different approaches (Warnecke and Huser 1995). Additionally, a greater scope of the company's management is delegated to individual organisational units, since decisions are always made at the level where the problem originates (Sihn and Briel, 1997). They also select and use the best numerical optimization techniques in a bid to find an optimal solution. (Venkatadri *et al.* 1997) proposes a fractal layout whereby cell competency may be enhanced through an iterative algorithm that constantly updates the fractal layout and improves the system by making it flexible enough to accommodate wide variety of products.

4.3.2.2 Dynamic restructuring

Reconfiguration is one of the main issues for adaptively changing the organisational structure when new situations occur such as the changes of product, production capability, shop layout, and other serious disturbances including machine breakdowns (Ryu *et al.* 2006). The operational self-organisation method, also called dynamic restructuring supports the reconfiguration and reorganisation of logical network connection between fractals and the reorganisation of fractals in the system (Ryu and Jung 2003) as shown on (figure 4.4). Although traditional control architectures have endeavoured to demonstrate re-configurability of a manufacturing system, they are not accurate enough to meet the requirements of circumstances such as high-level autonomy in reconfiguring the system architecture (Ryu *et al.* 2006). Moreover, they also take longer time to respond to unexpected events and are not fault tolerant (Frayret *et al.* 2004). The strategic and tactical component of the self-organisation aims to achieve global objectives locally. It stresses that not only procedures, but also processes of structure formation require dynamics in an unstable environment. In figure 4.4, when disturbance occurs, there is re-organisation of logical connections of controllers, regardless of their hierarchical position. The self-optimization module prompts Fractals A and B of the necessity for reconfiguration. The fractals (A&B) first change the network connections based on the frequency of interactions, creating new fractals (A, B & C) and reorganise their structures to more stable fractals by the dynamic restructuring process. Dynamic restructuring of processes in fractal organization enables its rapid adaptation to varying environment changes (Shin *et al.*, 2008). Restructuring the fractal units enables issue of process cost and product pricing to be controlled. Simulation-based restructuring model of production BFUs contain all functions of manufacturing organisation and implementation and can reconfigure the system without interrupting operations of existing components.

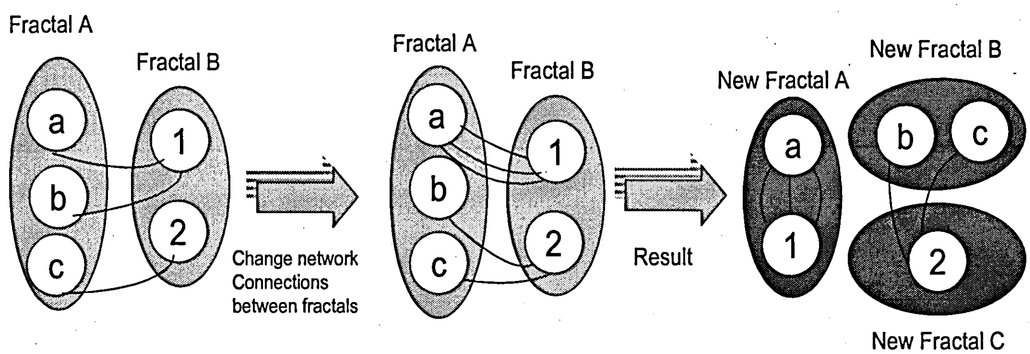

Figure 4.4 Dynamic restructuring process in fractals (Ryu and Jung 2003)

The Dynamic Restructuring Process (DRP), is described by Ryu and his colleagues (Ryu *et al.* 2006), including the concept, procedures and working mechanism. Metamorphoses of fractals are included in the boundary of reconfiguration in the FrMS. This includes generation, movement, and disposal of fractal agents, generation of new fractals and disposal of existing ones. Self-organisation is embodied through the DRP, which supports autonomous reorganisation of system configurations (Ryu *et al.* 2004). Ryu and Jung (2006) make the case that the FrMS has no pre-defined structure of fractals and the function of each fractal can be dynamically changed according to the variation of topological phase in the hierarchy of fractals. However, it is not the function of these fractals that change during DRP, but rather the control object of the fractal that gets replaced. The DRP capability enables the reorganisation of logical network connections between fractals so that the FrMS is able to adapt and react to dynamically changing environment with the least human intervention. In their algorithm, (Mun *et al.* 2004), established a step-by-step dynamic reconfiguration procedure, as a recursive computational process with finite number of steps. It is invoked by malfunction of some equipment or machine. This set of unambiguous instructions is performed in a prescribed sequence to address software architecture for implementation. Ryu *et al.* (2004) designed a real-time simulator for facilitating the DRP. It autonomously triggers

DRP by enabling fractals to decide whether to perform the DRP or not and when to begin the process. It also acts as an evaluator for the level of satisfaction of the DRP, improving the overall self-reconfiguration performance of the system. When the DRP is done, there is evolution of groupings of independent and vital fractals in the interest of serving the whole company and it enables rapid adaptation to changes and disturbances in the environment (Shin and Jung 2007). The DRP of the FrMS can be triggered by the following internal/external events; breakdown or recovery of an equipment, change of goal, overburden of a fractal, change in products or production environment and addition or removal of an equipment (Ryu and Jung 2006). The FrMS while changing its structure dynamically and automatically during DRP at run time, the structure and strategy of fractals affect the system's efficiency and effectiveness (Mun and Jung 2007). In this scenario, the FrMS focuses on infra-factory problems, especially distributed manufacturing system control to cope with these unpredictable events.

4.3.3 Goal orientation

Each Agent in the fractal Manufacturing System (FrMS) generates, achieves and modifies its own goal automatically during the coordination process with other agents (Cha *et al.* 2007). Goals are the main controlling variables for the fractal organisation and are generated and modified through coordination between participating fractals (Warnecke 1993). The goals of fractals are unique and are somewhat different from that of other fractals. That is to say that every fractal in the FrMS has their individual goals. Goals in the fractal system mean system of goals. It is supported by an inheritance mechanism to ensure consistency. The FrMS must continue to develop goals autonomously in order to harmonise the system by resolving conflicts (Ryu and Jung 2003). The goal-formation process is a process of generating goals by coordination processes between participating fractals and modifying them as is necessary (Ryu and Jung 2003). Each fractal must have a coordinated, individual, current and consistent system of goals (Warnecke 1993).

The goal formation process can emanate from a given division independently. This gets modified through a feedback loop and is implemented. To achieve the goal of the FrMS, individual goals are developed in an iterative fashion and getting feedback after achieving each goal. The system of goals that arises from the goals of the individual fractals is free from contradictions and serves the objective of achieving corporate goals. There is also the freedom to map out individual route to achieving goals. Any conflicts that arise between competing goals are revealed and resolved reliably during the goal-formation process.

The classic state of conflicts which arise between exploiting capacity, reducing inventories, and minimizing the operating cycle are considered under the same classificatory division (Warnecke 1993). Such conflicts and contradictions are resolved and expressed within the system of goals. This then creates the goal profile and sets out the list of priorities.

The goal formation process is a control loop, roping in all participants. It also incorporates all relevant parameters; market requirements, technical restrictions e.g. finance and individual moral concepts. The organisation continues to develop autonomously. A fractal pursues its goals by cooperating with other fractals (partners). It generates its goals through the goal-formation process (GFP), automatically, and it determines its partners in a market-based negotiation process called dynamic restructuring process (DRP) (Mun and Jung 2007). This process can take place dynamically and automatically at run time.

To achieve its goals, the FrMS. performs operations with several fractal specific characteristics, through coordination and cooperation amongst its functional modules (Ryu and Jung 2003). The goal-orientation mechanism enables each BFU to autonomously generate and evolve its own goal (Shin and Jung 2007), and includes the following elementary processes as subordinate mechanisms, Goal generation process (GGP), Goal balancing process (GBP), and Goal Harmonising process (GHP) (Ryu and Jung 2004) through the goal formation process (GFP) (Cha *et al.* 2007).

4.3.3.1 Goal generation process, GGP

The GGP makes and propagates goals for all fractals (Cha *et al.* 2007). The internal status of the FrMS and the external environmental situations can significantly and dynamically influence the goal structure. Goals are structured so that a higher level goal has considerable effect on the lower level goal. GGP is the first stage of the GFP. This is set out in the goal formation mechanism proposed by Ryu and Jung (2006). Initially, during the process of goal propagation, the parent fractals consider which goals to allocate to their child-fractals are profitable for attaining its goals. The reference goal model is consulted, while the parent fractal generates interim goals for its child fractals. It considers the distinctive features of its child fractals while doing this. The child fractals then checks if the interim goals are appropriate to its status. If appropriate, the fractal then sets its goals to the interim goal and propagates the goal to lower level (child) fractals. This process of goal propagation from higher level (parent) fractals to lower level (child) fractals is called forward propagation. Once the forward propagation is achieved, it proceeds until a given goal is propagated into the entire relevant subordinates and each acquires its own goals. Goals can be achieved on a real shop floor after being converted to plans or tasks. However, conflicts occur as a result of variations made during processing jobs or through unforeseen occurrences like machine failures.

4.3.3.2 Goal harmonization process, GHP

The GHP eliminates or reduces possible conflicts and interferences between goals generated in the GGP (Cha *et al.* 2007). The GHP is the second stage of the GFP. It kicks off at the termination of the GGP. (Shin *et al.* 2008) proposed the algorithm for the GHP and set out the mechanism for detecting and resolving conflicts during the GFP in the FrMS. These processes of detection, resolution or elimination of conflicts as well as the reduction of interferences of goals are achieved through negotiation and coordination of goals. Fractal goals are in harmony with the global goals. Hence, goals of a fractal may occasionally conflict with those of other fractals since fractals have no information about how other fractals make a decision on the basis of their own local knowledge. If this situation arise and the conflict is detected, relevant goals are revised in a bid to resolve the conflict. In an adverse scenario, the revised goals may become disharmonious with other fractal goals, hindering the achievement of the goal of the parent fractal. This situation is forestalled by the parent fractal by considering changing the child fractal's goals and if necessary, revising its goal. This is by way of propagating the changes in the child fractal's goal into its parent fractal. This process is known as backward propagation. During backward propagation, the process of propagation of goals between the child and parent fractals goes back and forth. The GBP uses quantifiable indicators of the manufacturing system to make compromise between goals.

4.3.3.3 Goal balancing process, GBP

The GBP takes place after the GHP. This is the final stage of the GFP. It refines the fractal's goal, after conflicts have been resolved during the GHP, to enhance the global performance of the entire system rather than maximisation of local interests (individual fractals) (Cha *et al.* 2007). GBP is one of the most important components of the GFP in the FrMS. Cha *et al.* (2007) proposed a coordination architecture and mechanism for the GBP. This architecture is based on multi-agent system (MAS) approach (Durfee and Montgomery 1994) where it is assumed that agents are not centrally designed and only cooperate with others if they stand to benefit from the cooperation. It also adopts the distributed problem solving (DPS) approach where agents are designed to improve the system performance, scalability, modularity, and reliability through cooperation with other agents to solve the global system problem. The earlier stages of the GFP focus mainly on the efficiency of fractal performance and utility. There is competition amongst agents for limited and shared resources. A compromise between fractal goals is required to enhance the global performance of the goal structure. The main aim of the GBP is to modify individual fractal goals to enhance global performance and to reduce the biased workload of each fractal for the stability of the entire system (Cha *et al.* 2007). The GBP involves sequence of events in which the parent fractal modifies the child fractal's goal. There are two categories within the GBP. The first order balancing category applies to cases where the parent fractal strengthens its goal by balancing its children's goal. This is achieved by relaxing the goal of the child fractals. The second category relaxes its goal for the overall global goodness of the system. As a result, it decides whether to strengthen or relax its goal. The basic unit of the GBP is called a unit goal-balancing process (UGBP). It involves the parent fractal and all of its child fractals. The overall GBP is achieved by series of UGBP. This process is recursively propagated to lower level fractals. A child fractal in the UGBP becomes a parent fractal to fractals below it in the hierarchy in the next UGBP.

4.3.4 Vitality and Dynamics

Vitality means that fractals have the ability to constantly adjust their positions to discover and take advantage of success factors and opportunities in the face of changing environmental influences (Warnecke 1993). Vitality is a concept drawn from the field of biology/ medicine to depict or describe the decisive behavioural characteristic of an agent in the FrMS, from its birth to its death (Ryu and Jung 2003). During its life time, fractals iteratively correct their relations and goals by cooperating and negotiating with others. The key issue for strategic operations of the FrMS lies in finding the optimal lifecycle of fractals. Buoyed by their strengths and the corresponding requirements to be met, they swiftly adapt and react to external influences, organising themselves into vital elements, independent of external pressures for the interest of the whole enterprise. Fractals also interact amongst themselves. The cooperation and coordination between self-organising fractals are characterized by high individual dynamics and an ability to adapt to constant dynamically changing environment (Ryu and Jung 2003). Dynamic structuring is underpinned by the interrelationship between them. To meet ever-changing environmental requirements, (Warnecke and Huser 1995) warns that the forming processes of organisational structures must be highly dynamic. The self-organising control loops makes the fractal company face up to the changes in the business environment coming from outside and sees them as competitive opportunities rather than disturbing variables (Shin and Briel, 1997; Shin *et al.* 2008a).

4.3.5 Navigation and Control

Fractals are in the habit of constantly checking and updating their positions within the target area. Fractal navigation and control use a 'check and balance' approach in reporting and correction of errors, and in controlling/ co-ordination of corporate activities. For continuous structuring processes, fractals require suitable navigation and control dynamics to determine their position and to direct their continuous development.

4.4 The Basic Fractal Unit, BFU.

From a module composition perspective, the fractal is also called a Basic Fractal Unit or BFU. The BFU is the main component of the Fractal Manufacturing System, FrMS (Ryu and Jung 2003). It consists of five functional modules, namely; an observer, an analyser, a resolver, an organiser, and a reporter. The FrMS performs operations with several fractal specific characteristics in order to achieve its goals, through coordination and cooperation amongst these functional modules (Ryu and Jung 2003). Tirpak *et al.*1992 applied the characteristic of fractal structure, namely recursive self-similarity, to the design of a complex system, modelling and controlling a Flexible Manufacturing System, FMS using the Fractal architecture. The BFU manages the structural complexity and coordination of a FMS hierarchy by maximizing local functionality and minimizing global control. They (Tirpak *et al.*1992) considered a FMS as a hierarchical organised entity which consists of several work cells, each containing one or more transporters and sub-cells, and found that, cast in a fractal architecture, the model of the FMS conforms to a natural hierarchical decomposition of highly decoupled units with similar structure and control. Figure (4.5) shows the essential structure of the basic fractal unit used to construct fractal architecture of a FMS. It is essentially designed to embody the elements that fully describe the structure of any level in the FMS hierarchy and its coordination with adjacent levels. According to (Tirpak *et al.* 1992), the typical unit interacts with a super-unit (the next higher adjacent level in the hierarchy) by accepting from it incoming jobs through a corresponding output port. At the input queue there is an inhibit flag that enables the unit to regulate the flow of incoming jobs from the super-unit. Inside a unit is a set of N sub-units whose internal detail is essentially hidden. Each sub-unit interacts with the unit by accepting from it partially finished jobs via the sub-unit output queue. The unit also regulates the productivity of one or more sub-units by controlling the states of corresponding inhibit flags, and influences it further by invoking priority directives. M transporters are an important set of resource of a unit that are responsible for delivering partially finished jobs from queue to ports (within the jurisdiction of the unit), according to a control policy generated locally and in coordination with the super-unit. Observation, evaluation, and control of the units operational profile is supported by a body of on-board software. This analytical and control software consists of four modules; the observer, the analyzer, the resolver, and the controller. The observer monitors the state of the unit, to access state information from its subunits, and to transmit the composite state information to the super-unit, as necessary.

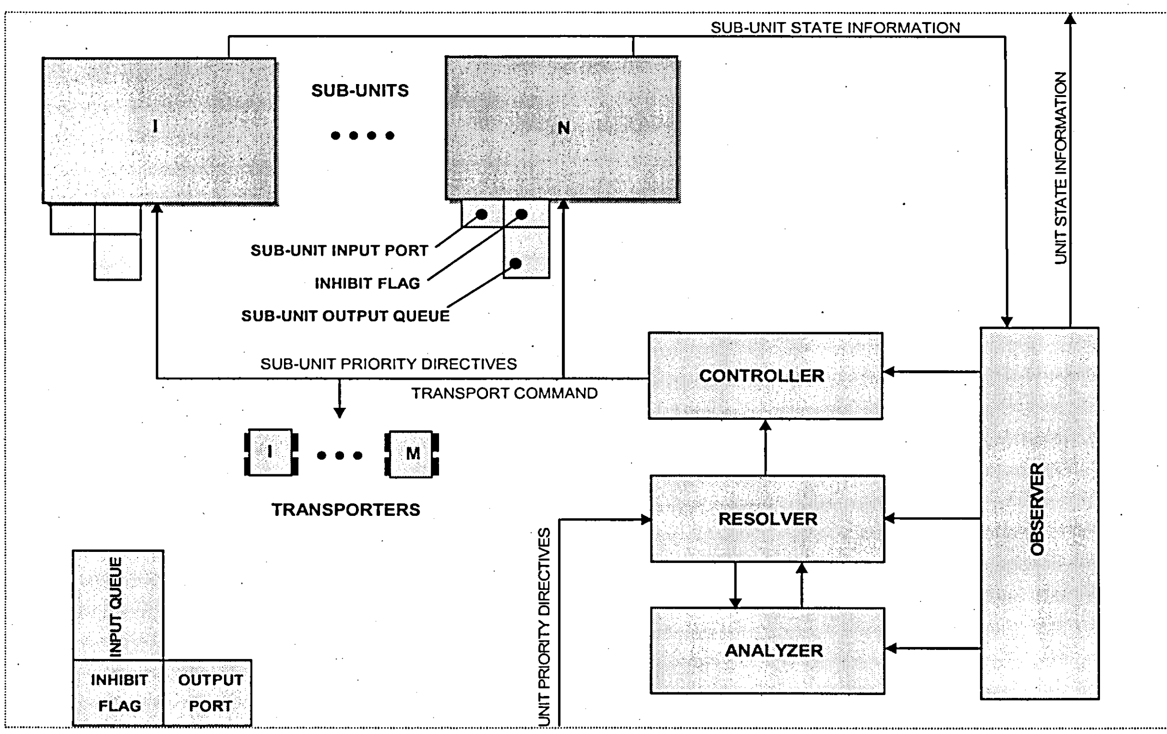

Figure 4.5 The Basic Fractal Unit (adapted from Tirpak *et al.* 1992)

The software is also responsible for running autonomously in the background, informing the unit about the condition of its resources and posting warnings that may include requests for maintenance or repair. Another part of the software in the observer is designed to run interactively, providing detailed operational information in response to queries from human operators. State information is particularly important in driving a real-time simulator in the analyser, whose function is to generate statistical job stream profiles over a number of useful scheduling rules by means of a stochastic analysis and to assign to each profile quantitative evaluations in terms of meaningful performance indices (Saksena *et al.* 1984). The resolver works hand in hand with the analyzer. It uses information produced by the analyzer to derive a set of recommended actions, under the constraints of the state information in the observer and the priority directives from the super-unit. In specific terms, the resolver may call for a variety of numerical optimization and/or heuristic techniques to prioritize these actions. To add to the versatility and reliability of the overall FMS performance, it is also possible to combine into the decision making process, at the resolver, the expertise of human operators (Davis 1989), whose interaction may be filtered from upper-level requirements to produce unit-level priority directives. (Davis *et al.* 1990) reports on a similar concept of the resolver implemented for the IBM logistics management system (Sullivan and Fordyce 1990).

The design of the BFU is clearly representative of any level of the FMS hierarchy. Evident from the above description is a highly localized functionality and a loose coupling to adjacent levels for intervention, coordination, and control (Tirpak *et al.* 1992).

Thus a BFU embodies the elements that fully describe the structure of any level in the FMS hierarchy and its coordination with adjacent levels (Shin and Jung 2007). The BFU comprises a set of sub-units, each of which is another BFU and of which internal details are essentially hidden, and a set of transporters responsible for delivery within the extent of its control. The architectural model of fractals represents a hierarchical structure built out of the elements of a BFU, and the design of a basic unit incorporates a set of pertinent attributes that can fully represent any level in the hierarchy (Tirpak *at al.* 1992). Each BFU provides services with an individual goal and acts independently. The BFU or the fractal develops its goals independently with equal right with other fractals, while resolving conflicts through corporation and negotiation. Other endeavours in this area include the presentation of a framework for embedding expert systems within an object oriented simulation environment by (Zeigler *et al.* 1996). (Zeigler *et al.* 1996; and Cho and Zeigler 1997) formulated a design technique for generating a recursive system entity. They showed how fractal architectures for flexible manufacturing can be specified using a recursive system entity structure. (Askin *et al.* 1999) treats the fractal layout as an extension of the cellular layout. Each fractal cell is a multifunctional mini-shop composed of contiguous workstations (Venkatadri *et al.* 1997 and

Montreuil *et al.* 1999). Askin *et al.* (1999) and (Saad and Lassila 2004 & 2006) did extensive studies on the fractal layout, proposing various fractal cell configuration methods for different system design objectives and constraints. However, these studies on facility layout design are restricted only to a set of machines and products. They did not extend to the entire organisational arrangements. (Hall 1998) applied the fractal architecture to study system engineering methodology. He asserts that the system engineering process has fractal architecture and this makes it more effective. He also identifies a logic structure of the systems engineering process as the BFU, which repeat in not only every phase and spatial level but also any field of knowledge.

4.5 The Fractal functional modules

Distributed, agent-based architectures prove viable alternative to hierarchical, centralized systems equipped with reactive/ proactive capabilities (Kadar *et al.* 1998). Traditional computer integrated manufacturing (CIM) systems are often very rigid, highly centralized and maybe suitable in steady state but are not robust enough in dynamic or unpredictable environments. Multi-agent architecture replaces the centralized database and control system with a network of agents with local databases and advanced communication capabilities (Kadar *et al.* 1998). This leaves the system with an open-ended global performance that develops through the dynamic interactions of agents in real time (Van Dyke Parunak, 1996). Distributed problem solving (DPS) and multi-agent systems (MAS) are two main areas of distributed artificial intelligence (DAI) (Bond and Gasser, 1998). Tasks/ problems are divided among a number of nodes that cooperate and work together in sharing knowledge about a problem and its solution in DPS. A distributed system is a collection of collaborative agents that can be seen as an organisation (Fox, 1994, Kadar *et al.* 1998). MAS deals with the behaviour of a collection of autonomous agents aiming at providing solutions to a task. It is a loosely-coupled network of problem solvers, working together to solve a problem that is beyond their individual capabilities (Durfee *et al.* 1989, Kadar *et al.* 1998). DPS and MAS are closely related and obviously share common grounds. The main component of the FrMS, the BFU (see subsection 4.4) consists of five functional modules: an observing module (observer), an analyzing module (analyser), a resolving module (resolver), an organising module (organizer), and a reporter and other auxiliary modules (Ryu *et al.* 2001, Ryu *et al.* 2003a, Ryu and Jung 2003). (Figure 4.6) shows the relationship among functional modules of the bottom level fractal. These modules autonomously cooperate and negotiate with others while processing their own jobs using agent technology (Ryu *et al.* 2003a). The FrMS performs operations with several fractal-specific characteristics in order to achieve its goals through coordination and cooperation among these functional modules (Ryu and Jung 2003). In the system structure, the BFU can fully represent the elements at any level in the hierarchy and its cooperation and integration with adjacent levels. At any level in the hierarchy, fractals have the same functional modules to aid their operations and for achieving their goals in conformance to the self-similar integral characteristic. The observer and reporter act as a gateway for communication with other fractals. The five functional modules work together in the system through coordination, cooperation and negotiation to achieve the shop level goal.

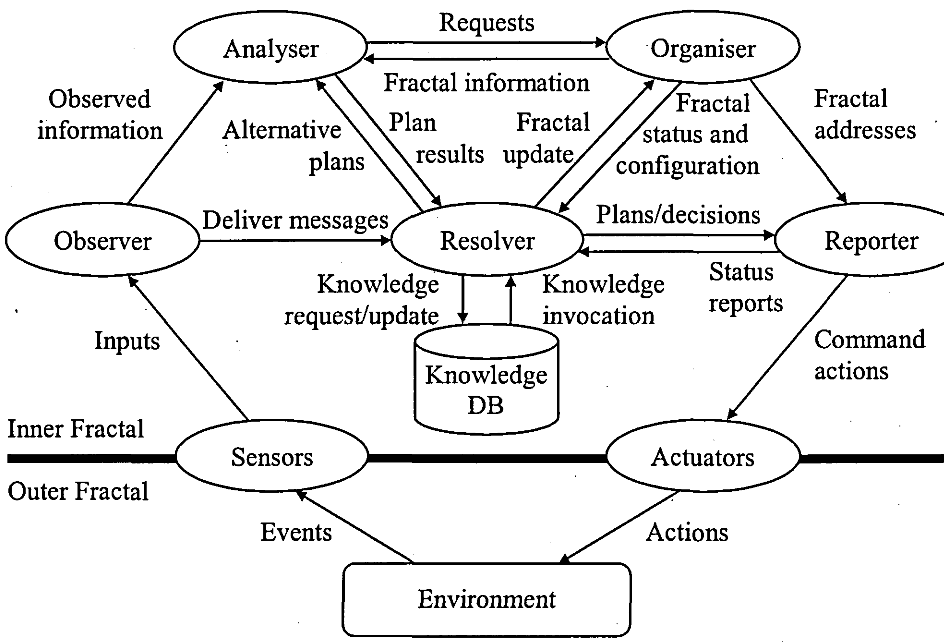

Figure 4.6 Fractal functional modules

4.5.1 Observer

The observer monitors the state of the unit. In conjunction with the reporter, the observer acts as a window for communicating with other fractals. It sends and receives messages and composite information to and from corresponding fractals. This might be upper, same or lower level fractals. The messages from corresponding fractals contain status information, negotiation or negotiation replies, job orders, incomplete goals or restructuring prompts. If the fractal is situated at the bottom level, the observer constantly monitors the equipment for sensory signals. These signals might for example indicate the completion of a job.

4.5.2 Analyser

Information on different alternatives of job profiles comes from the resolver. The analyser weighs and evaluates these different alternatives with status information, and simulate this profile in real-time. The best job profile is selected regarding the current situation of the fractal as a result. It also rates the dispatching rules for achieving its goals, such as earliest due date, shortest processing time etc. and decides which one is the best, with the status of the fractal involved, and the system of goal. It then scores the job profiles against the real-time simulation results. This is finally reported back to the resolver (Figure 4.6)

4.5.3 Resolver

The resolver plays the most important role among the functional modules. It has direct links with all the other modules. Its responsibilities include; generating job profiles, processes of goal-formation, and other decision-making processes. During the goal formation process, it modifies incomplete goals delivered from the upper level fractals, and makes the goal complete by putting the current situation into consideration. It also divides the fractal goal into several sub-goals for the sub-fractals. The resolver gathers information on the system goal and fractal status and incorporates these in the job profile creation with information on the configuration of sub-fractals. This is then sent for evaluation to the analyser. The resolver also optimises the goal formation process by employing numerical optimization or heuristic techniques for the overall fractal performance. The negotiation, cooperation and coordination processes are also initiated by the resolver and filters out unreasonable replies by pre-evaluation processes (Figure 4.6). Being the only module with access to the knowledge database, it invokes knowledge data at decision-making processes to build versatility and reliability into the entire system.

4.5.4 Organizer

The responsibilities of managing the fractal status and fractal addresses during the dynamic restructuring process, DRP rest with the organiser. The fractal status aids in analysing and selecting the best job profile among alternatives. It also creates negotiation replies to other fractals. While fractal addresses helps the reporter in locating physical address of fractal (e.g. machine name, port name, etc) in lower or same level on the network. This information is used to confirm the destination of tasks and messages. During fractal reconfiguration, numerical optimization techniques might be used for optimal configuration. The classic case of fractal workload re-balancing is done by the organiser. It initiates the DRP to reconfigure the workload to stabilize the system for efficiency and productivity and to avert unexpected errors.

4.5.5 Reporter

The reporter's main function is to act as a window through which fractals can report messages, tasks and results from processes to others. While the observer serves as an inlet, the reporter serves as outlet for communications. For the bottom-level reporter, the fractal acts as a traditional or conventional equipment controller, issuing command-like messages to control the hardware. The three types of messages generated by the reporter include; sub-goals for sub-fractals and messages for requesting the status of sub-fractals, negotiation replies and reports of the current status for the super-fractal and finally, the tasks in the best job profile. Functions of the reporter are relatively more trivial than that of other functional modules.

4.5.6 Miscellaneous agents

Several other agents are needed for the smooth running of the system in addition to the five modules. This includes the BFU agents that manage BFU-related operations for the DRP, such as the generation and deletion of BFU and evaluation of their utilisation/ performance. BFUs are created during a cloning mechanism. The system agent takes charge of device hardware and basic operating system of controllers. There is also the network agent that manages the network addresses of controllers in the system.

4.6 Fractal Layout

The fractal layout is concerned with issues of shop floor planning, arrangement and function layout. Fractal layout is proposed by (Venkatadri *et al.* 1997) and (Montreuil *et al.* 1999) and is seen as an extension of the cellular facility layout. They think that new generation of flexible layout is needed in an agile manufacturing system to cope with new and dynamic manufacturing environments that need to adapt to changing products and technologies, pressure for lead times reduction and inventories, product customisation etc. The formation of the fractal layout portrays a multi-functional mini-factory within a factory as an agile manufacturing alternative. The fractal cell composes of a set of neighbouring or contiguous workstations on the shop floor (figure 4.7) and is the basic unit of the organisation (Venkatadri *et al.* 1997). These workstations have about the same machine composition and are indeed very flexible in that they have the capability of processing almost all the jobs routed to them, making them a multi-functional mini-shop. The layout in the fractal arrangement starts with assigning workstations to cells in a uniform pattern, creating a roughly similar processing capacity in different regions. Travelling distances are also considerably reduced and enhanced compared to distances travelled by parts routed between processing departments in a large conventional factory (Askin *et al.* 1999).

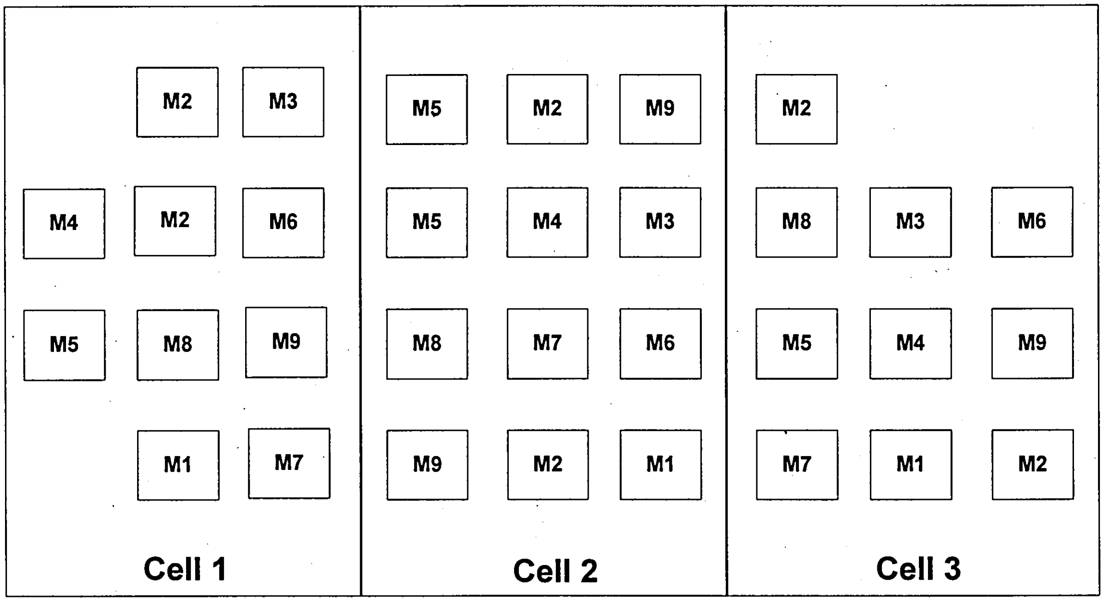

Figure 4.7 Fractal layout (adapted from Venkatadri *et al.* 1997)

(Venkatadri *et al.* 1997) incorporated a mathematical programming model of fractal cell and an iterative algorithm that arranges machines within the fractal shop floor and selects product routes for a known set of demands and process plan. The iterative algorithm continuously optimises the layout and flow assignment according to available resources. The results show that unrestricted product flow has the best performance in the fractal layout, though free routing over cell borders is required for minimisation of material handling distances. In their description of the fractal layout, (Montreuil *et al.* 1999) focused their attention on an extensive view and implementation of production system organisation. They realised that cells with identical machine composition and layout processed all products with the same efficiency and that material travelling distance is reduced by layout optimization. However, the capacity of each machine type is determined prior to deciding the number and composition of fractal cell. Reconfiguration of resources on the created shop layout is essential in an agile environment with highly changeable product mix and demand (Saad and Lassila 2004). They think that the assumption that all cells are identical might likely require resource duplication. The fractal organisation upholds the notion that process capacity is distributed evenly across cells. Machines may also be shared between cells, making the duplication effort optional. This contrasts to group designs where cell grouping is product oriented. (Askin *et al.* 1999) compares different layout designs in their simulation studies. The performance of fractal layout is compared with holonic and process layouts. The variable conditions considered include part routings, inter-arrival times and exponential operations based on queuing theory. Machines were located randomly within each fractal, i.e. cells were not specialised for any product. They found among other things that fractal cell is capable of processing all products, assuming they are of identical form and fully independent. Hence the fractal layout with a nearly square arrangement of machines performs better for agile manufacturing (Askin *et al.* 1999). They also demonstrated that material movements in the fractal layout are reduced by forming small multi-functional cells with short part routes. Their experiment was well received but being conducted on independent and similar fractals, where all cells had exactly the same composition of machines, they should have experimented with different, more realistic scenarios. However, the fractal layout is not without a setback. The multi-process functionality of the cells in fractal is more diverse and difficult to manage. The way round this problem according to (Venkatadri *et al.* 1997) is to define cells of core competencies (e.g. drilling machine, turning centre, and finishing centre with grinding and cooling capability) and replicating this throughout the shop floor. Then cell competency is improved through constant improvement of this core group, which is flexible enough to process a wide variety of products. A number of design issues also come to the fore in the fractal shop floor organisation; the flow assignment problem, which is how products get processed through particular machines, is a particularly difficult task in the fractal cell design. The processor layout problem is difficult owing to the multi-functional nature or variety of processes present in the cell. There is also issue of the cell layout with relation to each other which posses a problem because cells are not independent. To solve these puzzles, (Venkatadri *et al.* 1997) suggest a coordination design effort that looks closely at capacity planning, cell creation, product assignment, cell layout and global layout. The issue of capacity planning which is concerned with the delicate task of number and type of workstations to be made available is solved by employing capacities close to what is demanded by function layout implementation. The function layout enables dictation of minimum capacity, being considered to have highest equipment utilization. If cell cooperation is to be allowed, then global layout which is the external layout defining the position of cells in relation to each other needs to be considered. In their work, (Saad and Lassila 2004) considered and put forward extended fractal cell configuration methods for different system design objectives and constraints. This is based on the recognition that there are many interdependent design parameters that play a significant role on the structure and operation of the system, and are in harmony with the strategic goals of the organisation. These parameters determine the level of interaction between cells, the distribution of different product types among the cells and the similarity of cell capabilities. There is no single type of fractal layout that can be the optimal solution to the fractal layout design problem of every organisation (Saad and Lassila 2004). The authors identify seven distinct combinations of cell configuration methods from fractal cell parameters. The design classification as shown on (figure 4.8), deals with issues of managing the resource requirements and material movements. This ranges from distribution of products to the cells through cell creation, to inter- and intra- cell cooperation.

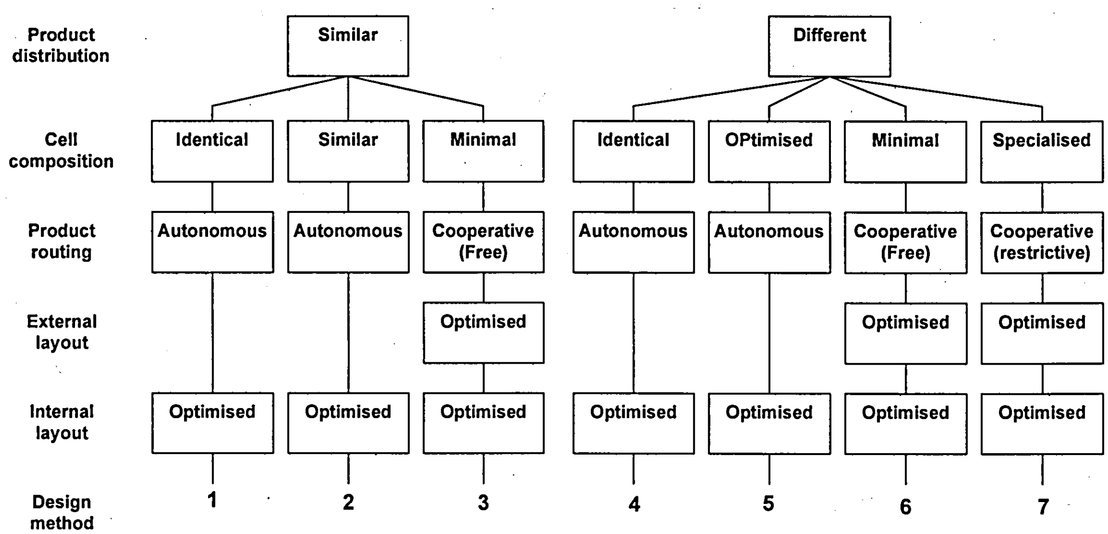

Figure 4.8 Fractal cell configuration methods (adapted from Saad and Lassila 2004)

Allocating machines to fractal cells is a complicated operation relating to capacity planning, cell similarity, and cell autonomy (Saad and Lassila 2004). Capacity planning must balance investment cost with operational benefits. A trade-off is required between processing capability or performance and adding more machines. The authors also noted the relationship between machine quantities and material travelling distances on the shop floor. A flexible layout is achieved by and large through optimizing product distribution and arrangement of machine and cells on the shop floor. On a general note, it needs to be stated that these various researchers have limited their studies on facility layout design for a set of machines and products, more work needs doing on incorporating these shop floor strategies into the general fractal organisational challenges.

4.7 Fractal Manufacturing System, FrMS

The FrMS evolves from the fractal factory introduced by (Warnecke 1993). The fractal factory was promoted by subsequent researches; (Warnecke and Huser 1995, Westkamper *et al.* 2000, Sihn and Klink 2001), but these works fell short of the practical operational features of constituent entities. They focused on the theoretical, organisational concept as well as the prominent potential features. (Ryu and Jung 2003, Ryu *et al.* 2003a) proposed the FrMS. Their work elaborated on the operational as well as organisational paradigm for manufacturing systems to build on the architectural characteristic potentials of the fractal factory, and the BFU model proposed by (Tirpak *et al.* 1992). Hence, the definition of fractal becomes modified to 'a set of self-similar agents whose goal can be achieved through cooperation, coordination and negotiation with others while being reconfigurable to a more efficient and effective structure' (Ryu and Jung 2003). The FrMS is then defined as 'a flexible, fault-tolerant, and self-reconfigurable manufacturing system developed and operated under the fractal architecture' (Ryu and Jung 2003). The fractal organisation is seen by (Shin *et al.* 2008) as 'a structured association of distributed entities in which a self-similar pattern is recursively defined or a system of fractals. FrMS develops and advances the conceptual principles for organising and designing with agent-based technology (Ryu *et al.* 2003a). The constituent features combine unique reactive/ proactive capabilities such as goal-orientation mechanism (Ryu and Jung 2004, Kadar *et al.* 1998) - for generation and achievement of main controlling variables or goals and dynamic restructuring mechanism (Ryu *et al.* 2006) - for self-reconfiguration of the functions of the system following internal or external events and management of complexity and changes. Fractals inherently have fractal-specific characteristics that are congenital to them; self-similarity, self-organisation, goal orientation and dynamics. In addition, they also exhibit agent characteristics; autonomy, mobility, intelligence, cooperation and adaptability. Their mobile behaviour proves particularly useful in a distributed and dynamic system, enabling them to travel freely among the controllers in a system from one network to another, forming a sophisticated software entity that possesses an artificial intelligence (Ryu and Jung 2003). The basic building blocks of FrMS, the fractal consist of autonomous cooperating multi-agents. It composes of modules and hence it is called a BFU. The conceptual architectural model of FrMS represents a hierarchical structure built out of the elements of a BFU (Ryu and Jung, 2003). Each BFU has an individual goal while providing services and acts independently. However, for coherency of the global system, goal consistency is achieved through goal formation process supported by an inheritance mechanism (Tharumarajah *et al.* 1996). The design of the basic unit encapsulates a set of attributes that can fully represent any level in the hierarchy (Tirpak *et al.* 1992). This is an important factor when considering the specific structure as well as the local functionality of the level in the hierarchy and the coordination with adjacent levels. At the highest level, the fractal can represent an entire manufacturing system or a mere physical machine at the lowest level (Figure 4.9). It is specifically designed to represent the elements at any level in the system hierarchy and its interaction and cooperation with adjacent levels (Ryu and Jung, 2003). This conceptual structure allows for the development of goals independently with equal rights and conflicts resolution through cooperation and negotiation. The main research endeavours in the FrMS include: the reference conceptual architecture of the FrMS, made by Ryu and Jung (2003), defining and analyzing the function specification of the basic building block, the fractal and comparing the FrMS with other newer manufacturing ideas; BMS and HMS. Agent-based systems and technology in relation to the fractal organisation was described by (Ryu and Jung 2003a). They showed the fractal agents associated with each functional module and their behaviour model. (Shin and Jung 2004) formulated a negotiation protocol to integrate negotiation agents, in a mobile agent-based negotiation framework. The overall goal-orientation mechanism was formulated and investigated by (Ryu and Jung 2004) and extended into goal harmonising mechanism as well as conflicts resolution and elimination by (Shin *et al.* 2008 & 2008a). (Cha *et al.* 2007) worked on the goal-balancing relations, quantifying the measures used for making compromise between goals. The dynamic restructuring mechanism was explained by (Ryu *et al.* 2006), dealing with the reorganisation of logical network connections between fractals in the face of disturbances and renewal mechanism. The algorithm for self-configuration/ dynamic reconfiguration and the software architecture for implementation were proposed by (Mun *et al.* 2004). The application of the fractal system to supply chain was made by (Noori *et al.* 2000), where they introduced the concept of the fractal manufacturing partnership, FMP, a new collaboration between original equipment manufacturers, OEMs and their key suppliers. (Ryu *et al.* 2003a) worked on the framework for the e-Biz company management. In it, they described a fractal unit representative of an individual component in supply chains to the whole supply chain. However, implementation of these prominent features of the FrMS in the shop floor still proves elusive and problematic.

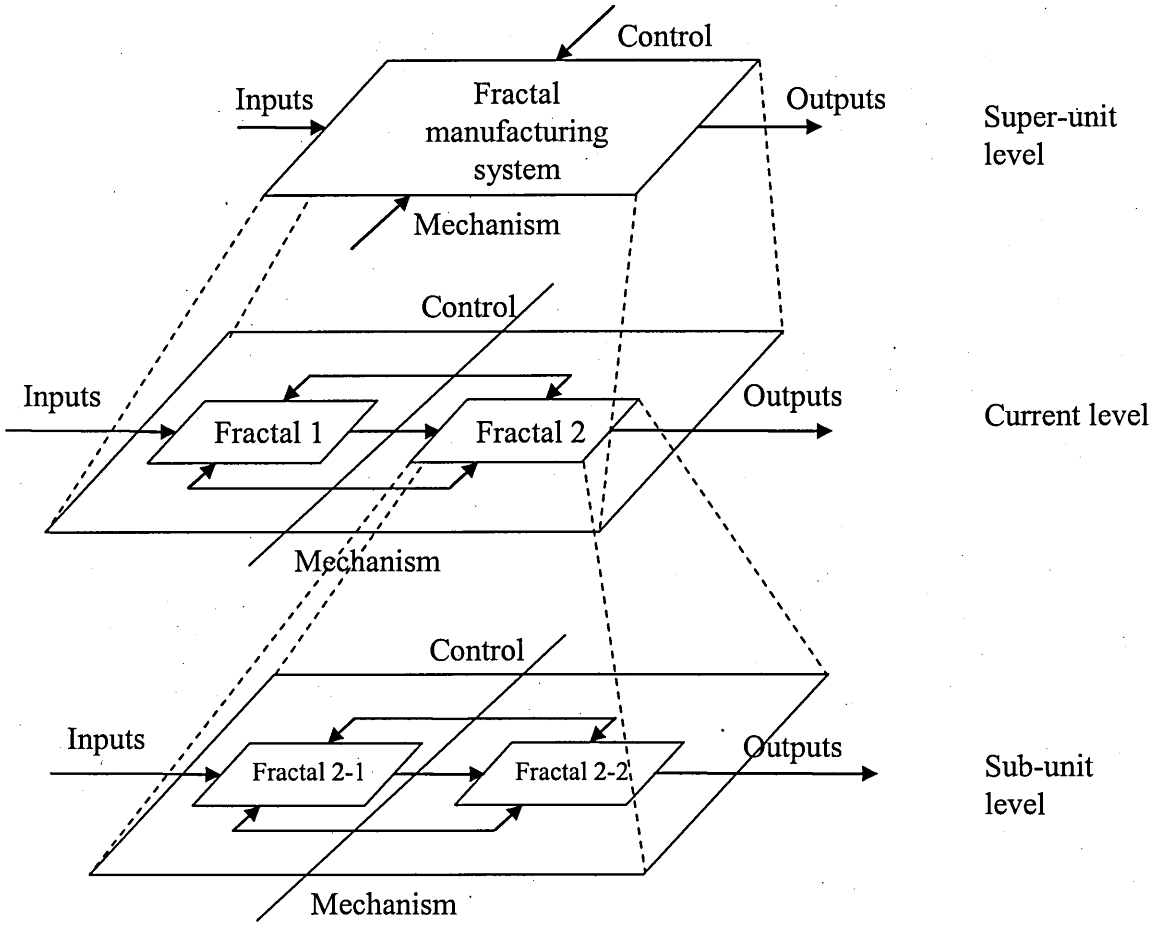

Figure 4.9 Fractal conceptual architecture (adapted from Ryu and Jung, 2003)

This is in part due to vague interrelations and interpretations among the constituent fractals, especially at the subordinate levels. For instance the responsibility of the relational entities in the parent-child relation is not clearly stipulated (Ryu and Jung 2004, Ryu *et al.* 2006). An attempt was made by (Shin *et al.* 2008a) to establish and reinforce the relational pattern specifications.

4.8 Distinctions between FrMS and Traditional manufacturing methods

The complexity of the manufacturing process stems from the integration of various production functions and management system that control and support the manufacturing activities to meet set goals/ targets which in most cases is the production of specified goods on schedule and at a minimum cost (Chase and Aquilano 1992). Company strategies and operational as well as managerial models influence design, planning, operation and control of the manufacturing system and definitely make the systems unique from one another (Wild 1993). There is sharp contrast and distinction between the way products are manufactured in the traditional system and how goods are made in the modern day system represented by the EMS (in particular Fractal Manufacturing System). The main differences are highlighted below on (table 4.1).

Traditional manufacturing method	**Fractal Manufacturing System**
• The company is structured once at a specific point in time (with external impetus)	• New environment that supports a real-time environment that moves faster.
• The company is the sum of its activities and strategic fields of business	• A technological change that deals with flexible manufacturing cells and systems, a hierarchy of controls that tie everything together, and the management information system.
• This manufacturing system is suitable in a stable environment. Processes are rigidly planned out	• Increased manufacturing flexibility.
• The company develops in a linear, stable and predictable as well as manageable and controllable way	• Variations in routing, operations, machines and operators.
• The organizational structure is a matrix hierarchy. Outlook is general, comprehensive and inflexible	• All three functions of management are affected: planning, implementation and control (Change is required throughout the organization).
• Certain departures from the plan are periodically corrected by new plans and compensated by holding resources in stock	• Absence of large inventory. Cycle stock is small. Safety stock is not used.
• There are clearly defined limits within the fields of the company and between company and environment	• Pull manufacturing approach - producing the exact quantity when needed.
• Information is handled according to its priority and momentary necessity, and this is based on division of labour (bring-principle)	• Primary tool: Team-based technology.
	• Degree of freedom- used in controlling the system and to react to unpredictable events: Machine failures, absence of operators, changes in the workshop environment.
	• Multifunctional workers (trained in different skills) involved in the process control; have responsibilities and authority to make decision on issues.

Table 4.1 Distinctions between traditional and fractal MS (Warnecke 1993)

While the traditional manufacturing system as the name suggests operates a static, tightly managed system, the fractal manufacturing system takes an open-ended holistic approach to production.

4.8.1 Critique of Traditional manufacturing

Detailed evaluation of the traditional manufacturing method was made in chapter two. It is not out of place to recapitulate the reasons why it has buckled under pressure in the 21st century here. It could serve perhaps as final word in this chapter. Advancement in technology has brought huge turnarounds in the 21st century, enabling the consumer to get involved in the production process through electronic means. Fast moving markets and technological leaps in the fields of digital technology, mobile telecommunication and broadband networks have all taken their toll on the traditional manufacturing method, overwhelming the system and consequently bringing it to its knees. This has happened due mainly to the following reasons;

- Due to its *Excessive rigidity*, the traditional manufacturing system has tightly structured organizational nature and hence is not equipped with capability to tackle production from supply chain point of view - from product ordering, product design, production and sales as well as the development of proactive and innovative technologies (Jordan and Michel 2000). This incapability makes it fall short of managing uncertainty, complexity and erratic customer behaviour.
- The traditional manufacturing system has *Hierarchical control architecture* which comprises centralised and hierarchical models. These are unable to cope with changing or unstable environmental demands because their decision making process is fully or partially centralised (Heragu *et al.* 2002). Coupled with this, they are either unreactive/ insensitive to unexpected events or their response is slow. There is also no safe guide against faults because they have very poor fault tolerance (Frayret *et al.* 2004) and no repair or replication capability.
- *Vertically linked or integrated organizational structure* with excessive bureaucracy. This structure does not inspire or encourage self confidence and autonomous performance on the part of staff. Entrepreneurial perception, thinking and actions on the part of all staff is not common or welcome. Hence company progress and development is predictable and continually linear. Economic arithmetic models are also static.

As a certain departing base, the pertinent detail to consider is the global common awareness for the changes needed in order to cope in the modern day with the ever more demanding volatile market. It goes without saying, the 21st century manufacturing problems should be solved with 21st century formula not with 20th century inflexible bureaucracy.

The next chapter details design of the fractal shop floor, emphasizing capacity level and cell composition.

Chapter Five

5.0 Designing the Fractal Enterprise

The fractal shop floor layout described in chapter four is designed in this chapter using the genetic algorithm approach, paying attention to determination of capacity level, cell composition and flow distances. Initially, the chapter discusses the general fractal layout design requirements including the aggregate steps. Then a general treatment of the Genetic Algorithm (GA) approach is made. Progress is made with the application of GA to the proposed design of FrMS shop floor layout and implemented using MATLAB. The chapter ends with discussion of the result and final conclusions.

5.1 Genetic Algorithm approach to designing the fractal manufacturing layout

The conceptual fractal shop floor builds up from individual cells and is capable of producing a variety of products with minimal reconfiguration (Venkatadri *et al.* 1997; Montreuil *et al.*, 1999). According to Askin *et al.* (1999), the fractal layout is an extension of the cellular layout. In fact, each fractal cell is a multifunctional mini shop (Venkatadri *et al.*, 1997). The fractal cell could produce most of the product types routed to it. This could let different fractals have layout specification that produce varied products. This decentralized production layout allows for flexible mass customization. However, there are many challenges posed by the design and implementation of this strategy. A design and simulation of the model of shop floor layout for Fractal Manufacturing System to determine the capacity level and composition of cells using a genetic algorithm approach is introduced here. The procedure is based on an iterative algorithm, implemented using MATLAB and used to calculate material travelling distances for each fractal cell and this continuously optimizes the layout and flow assignment according to the performance of these parameters and creating maximum space utilization.

5.2 Fractal manufacturing layout design

A good fractal manufacturing layout design forms the backbone of the entire process of FrMS modelling. It has to achieve the goal of minimizing investment and operational costs and maximize flow performances in a feasible fractal factory. The layout design process has to emphasize minimization of flow distance in order to increase the flow and layout performance satisfactorily (Montreuil *et al.*, 1999).

However, the fractal layout design poses numerous challenges. The core issues of fractal layout design involve various aggregate steps. These include; capacity planning, fractal cell creation, flow assignment and cell/ global layout (Venkatadri *et al.*1997).

5.2.1 Capacity Planning

The decision of the number of workstations for each machine types in fractal design is a very delicate one. Other very important issues include; material handling, systems design, machine reliability, parts scheduling, etc. These are all issues involved in the capacity planning process. Moreover, product routings, processing times, and workstation availability are important input data for designing fractal layout. Flow performance can be improved by reducing the implied flow distance. Cost of material transfer could be traded off against initial investment cost (Montreuil *et al.*, 1999).

The capacity planning task requires optimal value of input data to satisfy product demand, minimise investment and operations cost and go into production within the pre-specified production time.

5.2.2 Fractal Cell Creation

The number of fractal cells and workstation composition of each cell is very important. The number of cells in a fractal layout has to be equal to the workstation types with least representation. Each cell needs to contain exactly one replicate of workstation type. Then the rest are distributed among the cells. Fractal cells share workstations, but each cell has to be allocated with equal compositions. These identical cells are standardised and flexible. They can respond well to unpredicted incidents or events such as machine breakdown, mixture of product, and transferring devices (Montreuil *et al.*, 1999).

5.2.3 Flow Assignment

The satisfactory estimation of flow around the actual workstations is also of significance in the layout design. According to Askin *et al.* (1999), machines are located randomly within a fractal. The flow assignment involves the decision of getting the products processed through particular machines on the job shop. The assignment of products to flow paths minimizes travel distance if there are several products with specified machine type routing to be processed (Venkatadri *et al.*, 1997). Layout must be optimised for an assignment of flow to particular workstations (Montreuil *et al.*, 1999). Flow assignment can predict replicate-to-replicate traffic in detailed level (Venkatadri *et al.* (1997). But machines can be shared between fractal cells and duplicated in the fractal layout. The flow assignment experiment can be used to improve the layout repeatedly until a satisfactory layout is generated (Montreuil *et al.*, 1999).

5.2.4 Cell Layout and Global Layout

Cell layout refers to the layout of replicates within each cell. Global layout on the other hand refers to the layout of cells in the plant. Cells can be placed relative to each other so the entire job shop layout can be optimised. A method of multi-phase layout that consists of both cell and global layouts are achieved simultaneously. According to (Montreuil *et al.*, 1999), Quadratic Assignment Problem (QAP) is used to solve the problems associated with these. A large area for the factory floor is used based on machine requirements, partitioning it into fractal spaces created for fractal cells. Each individual cell layout is improved to take into account intra-cell and inter-cell flows based on QAP formulation. This process is implemented when the layout of one cell is being improved and is stopped when layout of other cells are frozen. (Montreuil *et al.*, 1999) used the QAP method to generate cell layout and global layout. In fractal factories, there are intra-cell and inter-cell interactions which make the fractal layout design really difficult. But, global layout is easy in the autonomous fractal factory. Once cell layouts are developed, they are then brought adjacent to each others in any desired manner (Montreuil *et al.*, 1999).

5.3 General layout modelling procedure

A set of general procedures are employed in the design of the fractal shop floor layout. There are two phases to this procedure;

(i) Design and simulate the model of FrMS shop floor layout using MATLAB R2008a, determining the machine types and machine routing sequence. Write MATLAB programming codes to minimize material travelling distances or flow distance score.

(ii) Apply Genetic Algorithm to continuously iterate and optimize the design of fractal layout and flow assignment according to the performance of these parameters.

5.3.1 Fractal layout problem (FLP)

(Azadivar and Wang, 2000) defined the FLP as "the determination of the relative locations for, and the allocation of the available space among a number of workstations". The resources could be different sizes and the interactions between resources may vary. This has been a concern for developing a block layout that represents optimal shape and arrangement of departments within a facility (Hicks 2006). Block layouts are usually represented in rectangles.

FLP is normally formulated as a quadratic set which covers linear integer programming problem, mixed-integer programming problem and graph-theoretic problem. Therefore, QAP formulation has been popular in this kind of problems. But manufacturing practice normally requires particular layout configurations such as single row, multi row or loop structures. These practical constraints place a huge restriction on the optimization process (Hicks 2006).

5.3.2 Fractal job shop layout

The fractal workstation layout is created to minimise the capacity requirements and material travelling distances (Saad *et al.* 2004). The fractal layout and flow assignment are optimised continuously using an iterative algorithm. (Venkatadri *et al.* 1997) proposes a layout design within a given flow assignment at the machine level. The core design process is initiated by capacity analysis and workstation allocation. Fractal layout is designed based on cell layout and global layout. In the design of the fractal layout, assignment of products to workstations depends on the distance taken from the layout in previous iteration. But the current iteration has to be better than the previous iteration. At each iteration, (Venkatadri *et al.* 1997) allow the column generation procedure to run its course and find an optimal solution to the flow assignment problem.

(Montreuil *et al.* 1999) argues that the fractal cells created must not necessarily be identical. But the standardized and flexible cell layouts are expected to respond well to short term changes such as machines break down, product mix, or transfer devices going offline. The process of cell creation that requires high investment within other manufacturing systems could be reduced in FrMS.

Additionally, (Venkatadri *et al.* 1997) suggest that the fractal cells are grouped in product types. Careful planning of workstations is of paramount importance. This could help to alleviate flow congestion of products and improve the flow efficiency. The flow score is measured and analyzed in order to estimate the function of frequency and distance travelled.

5.4 Genetic Algorithm (GA)

GA is one of various popular stochastic search algorithms. Just like evolutionary algorithms, it allows systems to self-adapt to make up for unpredictable changes in the operational environment. Most real world manufacturing problems are dynamic - they change with time. To deal with such problems efficiently and effectively, different fault tolerant structures are required. GA is one adaptable method used in solving problems in these dynamic operational environments.

5.4.1 Overview of Genetic Algorithm

According to (Kamrani and Gonzalez 2003), many combinatorial optimization problems in manufacturing systems are very complex and can not be solved using conventional optimization techniques. Therefore, evolutionary algorithms (and more specifically GA), a simulation of natural evolutionary process techniques have been introduced. GA would attempt to take into account a wider range of possible solutions and further increase the probability of finding optimal solution.

(Holland 1975) developed a heuristic search and optimization technique that is used to mimic the biological evolutionary process and natural selection process (Azadivar and Wang 2000). GA is a general purpose search method that combines elements of stochastic search for exploiting the search space to discover optimal solutions. It performs better compared to other stochastic searches due to its unique features of population-based search, independence of gradient information, implicit parallelism, and flexibility to hybridise with domain-dependent heuristics (Xiaodan Wu *et al.*, 2007). GA employs randomised choice operators in the search process and does not depend on complete *a priori* knowledge of domain features (Rajasekharan *et al.*, 1998).

It starts with a set of random solutions called population. The initial population has to be determined by the user of the algorithm. The population of potential solutions is initialised to the problem and better solutions are searched and produced by combining the existing individual strings by using one or more genetic operators (Rajasekharan *et al.*, 1998).

According to Goldberg (1989), a chromosome is a string of binary bit which represents the solution to the problems being solved and discussed. The solutions have to be represented accurately in order to obtain useful final information (Kamrani and Gonzalez 2003).

Chromosomes evolve through iterations called generations. The decision for chromosome to either continue or exit the next generation is evaluated using fitness function. During each iteration of GA, there would be a new generation created with new chromosome called offspring (Kamrani and Gonzalez 2003). The offspring are formed by merging two chromosomes from current generation using crossover operators. Besides, the offspring could also be created by modifying a single chromosome using mutation operators. After a few generation of GA, the best chromosomes represent the optimal solution to the problem (Holland 1975).

5.4.2 Genetic Algorithm procedure

As a powerful and broadly applicable stochastic search and optimization technique, GA has successfully been applied in various areas which include the Facility Layout Problem (FLP) (Azadivar and Wang 2000).

The layout design tools that are used in this modelling can solve the overall layout problem as a hierarchically organised set of cell design problems. Factory layouts are optimised by minimising the direct travelling distance amongst the machines. The design tools are integrated into a sophisticated simulation model that can be implemented in facility layout problems (Hicks 2005). In order to employ GA to search for the best solution of facility layout problems with various kinds of machine types and product types, the general steps that are shown in (Figure 5.1).

The FLP is a combinational problem for which the optimal solution can be found for small problems. GA based search is one of the good method for dealing with problems of facility layout. In the GA approach to optimization, feasible solution to the problem is encoded in data structures in the form of a string of decision choices that resemble chromosomes. GA maintains population of chromosomes or individuals that are created. The layout design is characterized by chromosomes' fitness which is measured by its value of objective function. Offsprings are created through reproduction, crossover, and mutation (Balamurugan *et al.*, 2006).

5.4.3 Genetic Operators

Crossover and mutation are the two genetic operators that are applied probabilistically to create a new population of individual strings (Rajasekharan, 1998). Crossover is an important operation performed by GA for solving combinatorial optimization problem. Two of the individual strings in initial population are selected randomly as two parents. A cut point is randomly chosen within the parent strings (Kamrani and Gonzalez 2003).

5.4.3.1 Crossover

Crossover operation exchanges cross sections of the parents in order to form two offspring. As shown in (Figure 5), the two offsprings form new individual strings generated by combining the "head" of the first parent string with the "tail" of the second parent string and vice versa (Rajasekharan, 1998). The essential characteristic of crossovers is the crossover rate (CR) which is defined as the ratio of number of offsprings produced in each generation to the population size. A higher CR allows deeper exploration of solution space and increases the chance of achieving accurate optimal results. On the other hand, if the CR is too high, it results in wastage of computational time (Kamrani and Gonzalez 2003).

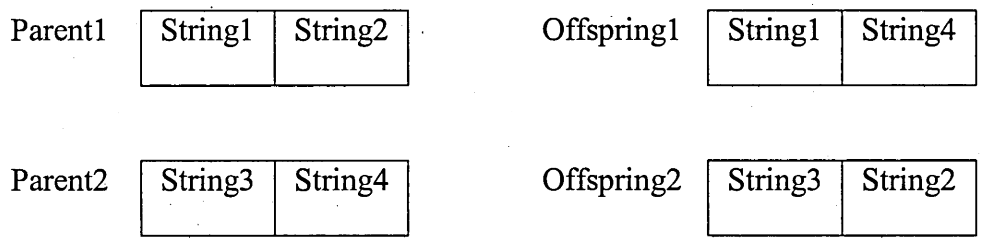

Figure 5.1 Crossover (Al-Sultan *et al.*, 1997)

Due to the unique hierarchical chromosome scheme used, a one-point crossover is used as in (Xiaodan Wu *et al.*, 2007). A cut point is randomly selected over the whole chromosome as shown in (Figure 5.2). Parent1 and Parent2 are the chromosome pair selected for the crossover operation. The "head" of Parent1 is replaced by "tail" of Parent2. Then Child1 is generated. On the other hand, the "tail" of the Parent1 replaces the "head" of the Parent2. Child2 is then created.

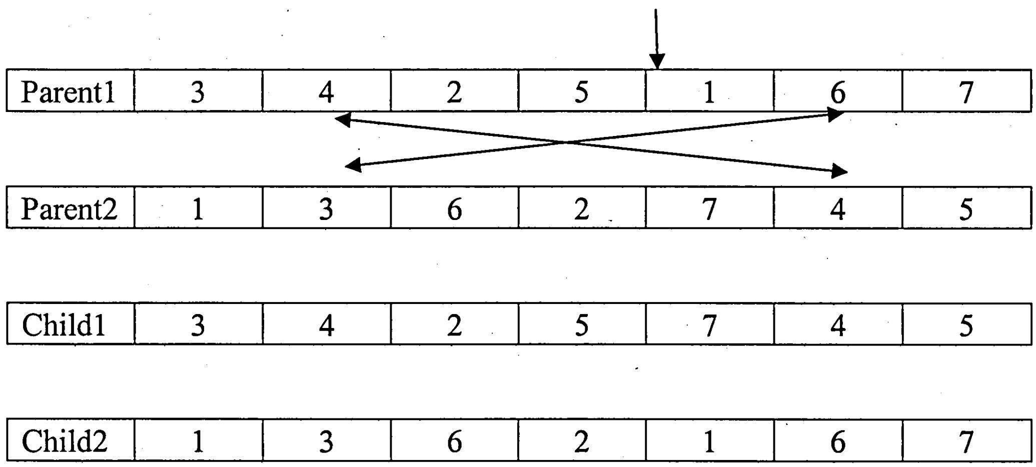

Figure 5.2 Numerical illustration of Crossover (Xiaodan Wu *et al.*, 2007)

5.4.3.2 Mutation

Mutation operation produces spontaneous random changes in certain chromosomes. Mutation play two roles that involve either replacing the genes lost from the population during the selection process, or providing the genes that were not present in the initial population (Kamrani and Gonzalez 2003).

Mutation is designed to prevent premature convergence and to explore a new solution space Xiaodan Wu *et al.* (2007). But, the mutation operation alters and mutates one or more genes within the chromosomes of an individual rather than across a pair of chromosomes. There are two kinds of mutation proposed by Xiaodan Wu *et al.* (2007), which are group mutation (Figure 5.3) and inverting mutation (Figure 5.4). Group mutation is for exchanging genes of the same groups for the same layer at same time. On the other hand, inverting mutation involves exchanging the genes from the randomly chosen loci of the parent. Both genes are chosen randomly for the operation of mutation.

From a theoretical perspective, if the length of the chromosome for inverting mutation is long, the chances of finding the optimal solution in the near-optimal area is low. However, the group mutation can help to enhance the GA's ability of exploitation and converging rapidly to a promising region (Xiaodan Wu *et al.*, 2007).

(Al-Sultan and Fedjki 1997) illustrated in (Figure 5.3) that group inverting mutation begins with a selection of a parent, and randomly dividing into two strings. The two strings are then exchanged to get a new offspring. Group inverting mutation involves two steps - a random cut of the selected parent is generated and the two chosen strings are then exchanged to obtain a new offspring.

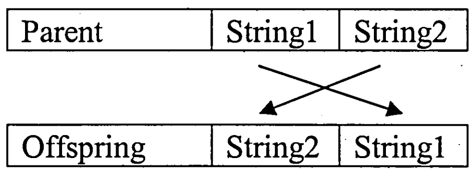

Figure 5.3 Group Mutation (Al-Sultan and Fedjki 1997)

According to (Hicks 2005), there is another kind of inverting mutation that involves the selection of the two points randomly and then the genes between those points are placed in reverse order. This inverting mutation is shown in (Figure 5.4). The other genes in other positions are also copied directly from the parent to the child. In an insertion mutation, a gene is selected at random. The gene is taken off from the chromosome and then inserted back in a random position (Parames Chutima, 2001).

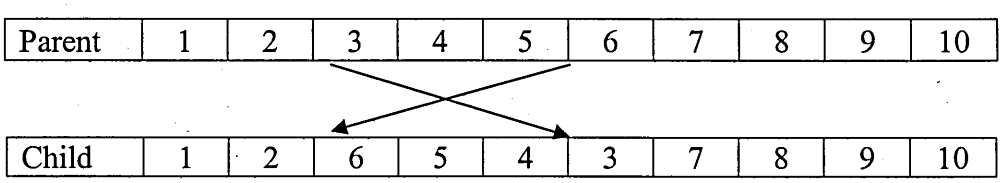

Figure 5.4 Inverting Mutation (Azadivar and Wang 2000)

5.4.3.3 Stopping Criteria

Two stopping conditions are employed to stop GA from iterating continuously (Parames Chutima, 2001). First, if the number of iterations exceeds the predefined fitness value, GA would stop the operation immediately. The other stopping condition happens if the value of the objective function does not change within the expected number of iterations. Once the algorithm has completed the given number of generations, it means that the best value of the objective function is obtained. At that moment, GA would be terminated and displayed with the layout configuration associated with the chromosome with the highest fitness value.

5.5 The proposed fractal manufacturing layout design

The initial fractal manufacturing layout is developed according to the configuration of cellular manufacturing systems by (Henry and Araar 1988). The proposed fractal manufacturing layout has been re-designed and reconfigured from the initial cellular manufacturing layout as shown in (Figure 5.5). Limitation of the cellular manufacturing layout includes inflexibility due to a fixed set of part families. Besides, cellular layout can only perform in stable environment and long product life cycles. It has limited allowance for inter-cell flows. Cellular manufacturing layout contains different types of machines and eventually increases the product inter-cell and intra-cell travelling distances.

The design by (Henry and Araar 1988) is implemented as the modified group layout and illustrate the process of constructing a fractal job shop. The example presented is a job shop with 15 distinct product types and 10 types of machine in the initial cellular layout. A total of 64 workstations are proposed by (Henry and Araar 1988) in the 6 cells modified group layout design within a factory. But, each group cell contains uncertain numbers of machines.

Montreuil *et al.* (1999) propounds that the grouping procedure implements a multi objective mathematical programming formulation with few surrogates;

- Minimize the difference between the assigned workload and capacity available.
- Maximize the number of products that are completed in each cell.
- Maximize the number of cells.

But, it is found that the objectives above are conflicting. The design for the group layout makes the job shop appear very much like a flow shop. But the group layout design suffers from the major disadvantage that requires too many workstation replicates (Montreuil *et al.*, 1999).

In this study, the GA approach lets us represent the entire group layout proposed by (Henry and Araar 1988) as chromosomes. The modified group layout by (Henry and Araar 1988) is shown in (Figure 5.5). MATLAB programming codes have made the representation of the machines in each cell easier. For instance, Cell1 can be represented as (1 5 2 6; 7 4 3 8; 9 10 3 5; 2 10 8 6; 1 5 9 10) in terms of MATLAB codes. On the other hand, Cell4 is coded as (3 9 2 8; NaN NaN NaN 5). (Where NaN means Not a Number in computing). Cell1 and Cell4 are combined using crossover operations. After the crossover, Cell1 is generated and it becomes one of the output cells for fractal manufacturing layout.

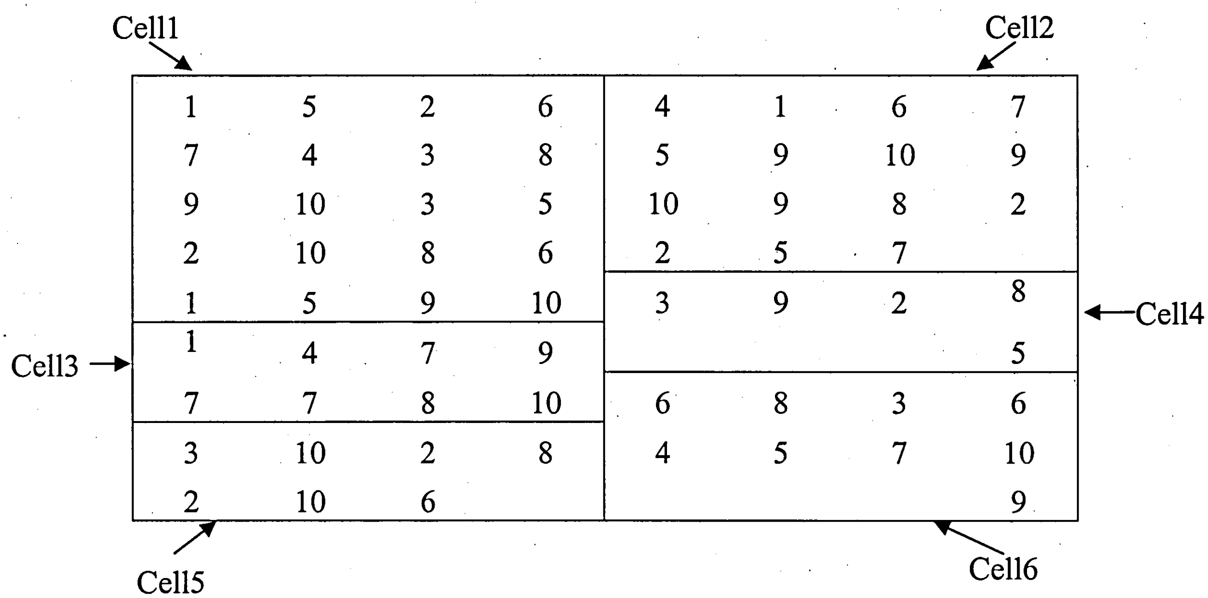

Figure 5.5 Modified group layout (Henry and Araar 1988)

Fractal cell is a set of neighbouring workstations on the shop floor (Saad *et al.*, 2004). The fractal manufacturing cell layout proposed by (Henry and Araar 1988) has a number of characteristics and is shown in (Figure 5.6). All fractal cells are similar and contain roughly the same composition of machines. Similarity of fractal cells in terms of machine types and quantities enable high efficiency in controlling shop floor, high operational flexibility and high flexibility for factory expansion. Moreover, all fractal cells are independent and are also capable of processing all products routed to them. Furthermore, products are distributed evenly among fractal cells.

The design for fractal layout (Figure 5.6) contains three cells. This choice leads to a cell population of 10 workstations, which is within tractable standards of 5 to 15 machines in each fractal cell. It is not necessarily to limit the number of workstations to 30 machines in this case (Venkatadri *et al.*, 1997). But, by adding few more workstations congestion could be alleviated and flow efficiency could further be improved. Therefore, it is logical and reasonable to increase number of Machine 7 in the following approach in the fractal manufacturing layout that is proposed by Venkatadri *et al.* (1997) and Montreuil *et al.* (1999).

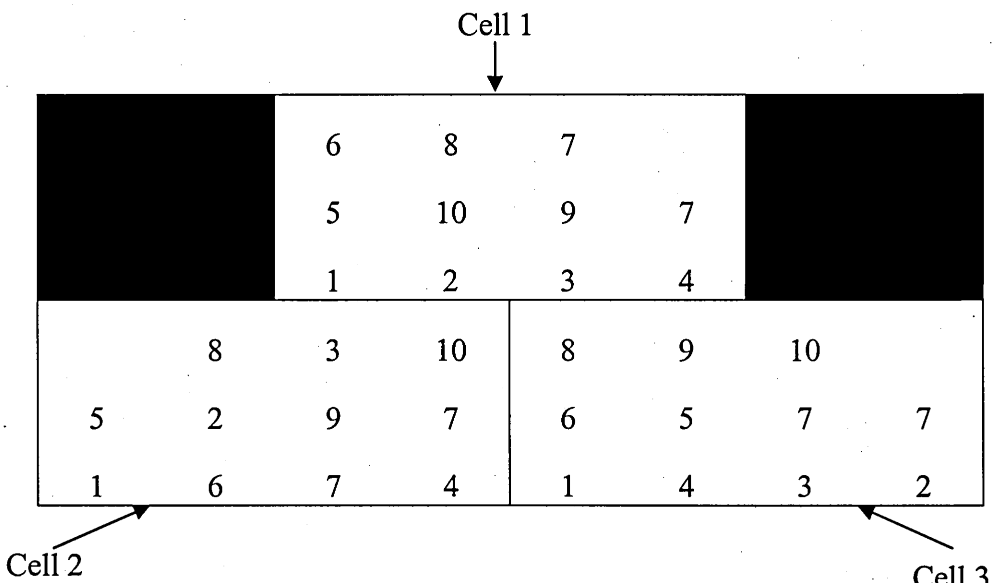

Figure 5.6 Fractal Manufacturing Layout

The goal of this process is to achieve a viable fractal factory layout configuration that could minimise investment cost and maximise flow performance. The expected fractal manufacturing layout that is shown in (Figure 5.6) has the advantages of;

- fewer total workstations than the initial manufacturing layout.
- higher flexibility to adapt to the changes of turbulent product demand.
- Each of the fractal cells within the layout contains all type of machines that are required to produce various kinds of products.
- Even distribution of product types among the fractal cells reduces the lead time of overall production.

Fractal characteristic of self-similarity can be observed within the fractal layout in (Figure 5.6). The three fractal cells in the fractal factory consist of similar, but not identical, organisational design structures. This is shown from the design parameter input such as machine capacity and product demand, and the output such as product travelling flow scores are identical for the 3 fractal cells. On the other hand, the fractal cells contain the same types of machines, but not the identical internal structures and arrangement of machines.

5.6 The proposed approach for Fractal Layout design

MATLAB R2008a is used as the programming tool in the fractal layout design. There are few approaches that are taken for designing fractal cell layout from the initial group layout. The steps taken in order to obtain a good solution are listed below.

5.6.1 Design Parameters

It is estimated that 10 types of machines are required in the fractal job shop. Machine requirement planning represents the beginning of the fractal layout process. This is carried out by computing the total number of hours required for processing the product demand (Montreuil *et al.*, 1999). There are 15 types of products that are required to be processed in the 3 fractal cells. Based on the bottleneck analysis, the total demand for the fractal layout is estimated to produce 400 products that can be processed in this fractal system without violating aggregate capacity constraints and respecting product demands. The other design parameters that are used for the fractal layout modelling have to be defined and calculated as below:

Machine types in fractal job shop = 10

Product types in fractal job shop = 15

Total demand = 400 products

Demand for fractal job shop = 400/15 = 26.67

Total machine processing times = 1108 minutes = 18.47hours

Machine processing times for processing the demand

= 18.47hours x 26.67

= 492hours

Total machine capacity (available hours) is 1297hours

Minimum number of machine required for fractal cell

= Machine capacity ÷ Machine processing times

= 1297 hours ÷ 492 hours

= 2.6 machines = 3 machines

Fractal decomposition is carried out using the procedures outlined in the section on cell creation design. The results of the calculation are shown on (Table 5.1). It can be shown that 3 machines are required for the 3 fractal cells. Therefore, it is feasible for each types of machine to be replicated or regenerated 3 times. The expected fractal layout contains 30 machines where each fractal cell has 10 machines.

Machine Type	Number of Replicates
1	3
2	3
3	3
4	3
5	3
6	3
7	3
8	3
9	3
10	3
Total	30

Table 5.1 Number of replicates for fractal cell layout

5.6.2 Input Data

Input data that are listed in (Table 5.2), (Table 5.3), and (Table 5.4), are the input data written in Microsoft Excel file. These input data are then imported into MATLAB programming codes for fractal layout optimization.

According to (Henry and Araar 1988) example on (Table 5.2), the routing sequence for the material to go through the machines that are required to produce each product of total 15 kinds of products. It is necessary that all the 3 fractal cells are capable of producing all of the 15 types of products routed to them. Machine processing sequences (Table 5.2) and machine processing times (Table 5.3), and workstation capacities (Table 5.4) are either been adapted or inferred from the original paper of (Henry and Araar 1988).

Product Type	Machine Processing Sequence									
1	1	4	7	3	10	8				
2	3	9	2	8	5	6				
3	2	3	4	5	9	10				
4	1	7	8	10	2	3				
5	5	6	8	1	4	7	9			
6	5	2	6	4	1	7				
7	6	4	5	7	10	9				
8	1	3	5	6	8	10				
9	3	4	2	1	5	9	10			
10	8	10	2	4	6					
11	3	1	9	5	7					
12	1	9	10	2	7	8	3			
13	4	3	10	2	8	6				
14	4	2	8	5	1	6				
15	1	5	2	6	8	3	4	7	9	10

Table 5.2 Machine routing sequence for 15 types of product

Product Type	Machine Processing Times (Minutes)									
1	10	7	20	15	8	17				
2	10	15	15	15	10	5				
3	11	13	20	15	12	10				
4	9	17	9	8	10	20				
5	9	7	7	15	15	12	9			
6	7	6	13	10	8	8				
7	7	13	12	19	14	13				
8	12	11	18	11	13	10				
9	6	9	8	17	20	12	13			
10	12	18	7	5	6					
11	13	12	9	8	11					
12	7	13	17	6	11	12	5			
13	13	20	5	15	12	17				
14	7	12	20	9	18	8				
15	20	12	13	13	13	5	7	20	7	5

Table 5.3 Machine processing times for 15 types of product

Machine Type	Machine Capacity (Hours) for each replicate									
1	25	15	10	30						
2	16	29	15	25	30	20	28			
3	17	15	40	30	10					
4	18	19	17	28						
5	15	20	30	20	20	20	30			
6	18	20	15	15	10	15				
7	10	20	20	10	15	20	15	15	15	10
8	20	20	15	15	10	10	10			
9	18	17	20	30	40	30	20	17		
10	20	10	10	10	30	30	30	15	15	

Table 5.4 Machine capacity for each replicate

5.6.3 MATLAB dialog box

A dialog box is created as an interaction tool on MATLAB. The dialog box pops up to request for input data as shown below. These data are used to verify the details from Microsoft Excel input files.

- The location of Microsoft Excel input file, sheet name of product sequence that is required for the modelling operation, and the sheet name of machines in fractal cell layout.
- The desired number of fractal cells that are needed.
- Number of rows and columns for each pair of initial cells that are required to generate each fractal cell.
- The cells required for crossover operation.
- The Desired number of iterations needed for generating the final fractal manufacturing layout.

The input dialog box (Figure 5.7) for file location and sheet name in Microsoft Excel has been used to ensure the location of the input data is identified and verified. The input dialog box (Figure 5.8) for desired number of cells is used to insert the number of cells that are required for the initial cellular cell layout. The input dialog box (Figure 5.9) is for the number of iteration needed to determine number of replicates and analyse the output of the flow distance score.

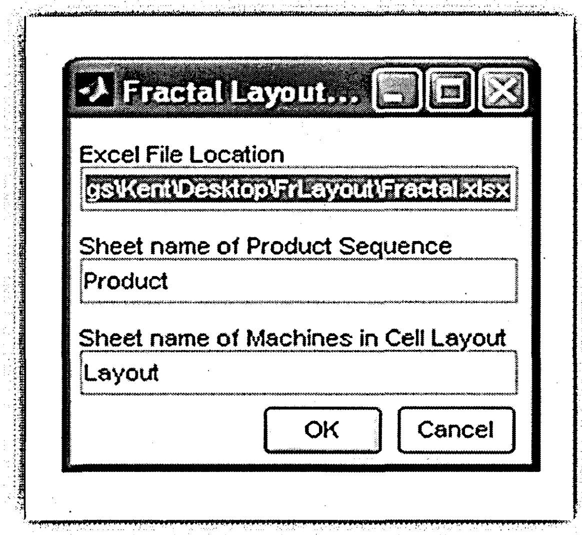

Figure 5.7 Input dialog box for file location and sheet name in Microsoft Excel

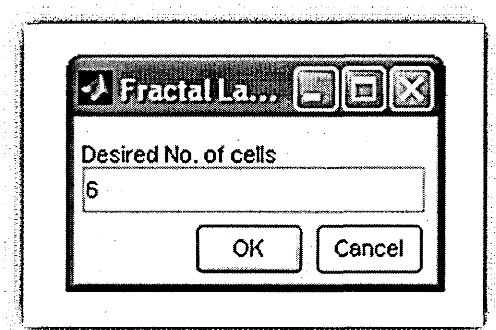

Figure 5.8 Input dialog box for desired number of cells

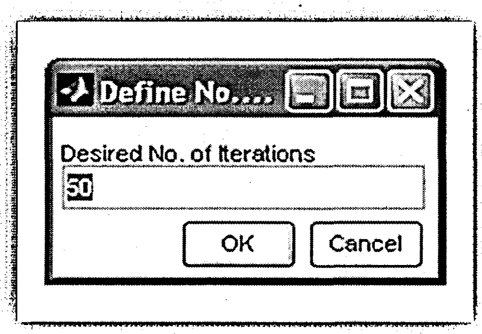

Figure 5.9 Input dialog box for number of iteration

5.6.4 Facility layout problem

According to Rajasekharan *et al.* (1998), the pickup point and delivery point positions of each cell are usually located on either one of the cell axes. In this model, the fractal cells are considered to be rectangular blocks with known dimension of (w, h) where w is width and h is height of each cell. After the crossover and mutation, the facility layout for FrMS for this model has a height, h of 3 rows and width, w of 4 columns. If the fractal cells are written as three rows and four columns in matrix form in MATLAB, then the Pickup Point is (1, 1) and Delivery Point is (3, 4) as shown in (Figure 5.10).

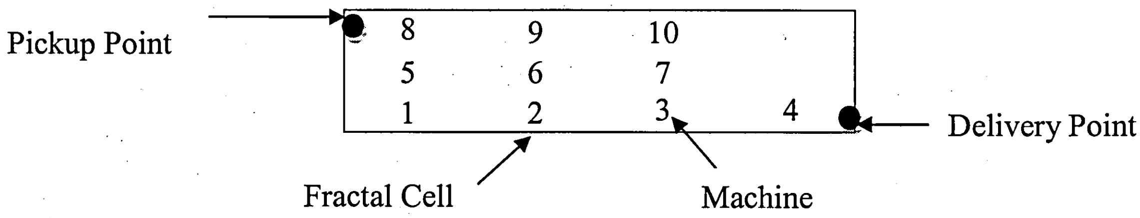

Figure 5.10 Facility layout problem for FrMS

Some logical assumptions are made for the facility layout problem. These include that the dimensions of the floor area on which the fractal cells are placed is given. The floor space for the flow path on the floor area is not considered. It is also assumed that the flow paths consist of segments that are horizontal and vertical to the walls of the floor (Hu *et al.*, 2006).

The fractal layout dimension, (3 x 4) is chosen because we are considering 10 machines during this modelling. Thus, it is required to generate at least 10 locations for the rectangular fractal cell layout. So, it is feasible to generate a facility layout with 10 machines and 2 spaces. This layout could reduce the material travelling distance by having multi-purposed machines in each fractal cells. All the inputs and outputs are the same. The only difference for the fractal cell is the location of each machine in the fractal layout.

5.7 Implementing the proposed Genetic Algorithm approach

An iterative algorithm is used to optimise the layout and flow assignment according to the design parameters. Products were assigned to workstation replicates in order to minimise travel distances within the fractal layout. The layout of each cell is refined using the implied flows between stations. The replicates are re-applied until the heuristic procedures could not find a better solution. The cells that are constantly iterated could obtain the optimal flow assignment to achieve the optimum fractal layout (Montreuil *et al.*, 1999).

GA is implemented to create a workstation layout that minimizes the material travelling distances and capacity requirements for product demand and mix. GA procedures - selection, crossover, row inverting mutation, column inverting mutation, and deleting mutation are included in the iterative procedures in order to generate the optimal material travelling distances. Each optimal fractal cell is selected based on its minimum flow distance score. Thus, optimum fractal manufacturing layout is created by combining the three optimal fractal cells.

The illustrations of the GA steps are presented by showing the first iteration of the fractal cell 1. Initial cellular layout is assumed to contain 6 cells. Fractal cell1 is generated by combining cell 1 and cell 4 by crossover operation. Cell 1 is shown as parent1 and cell 4 is illustrated as parent2 in MATLAB programming codes. Chromosomes for each Parent are represented by the various kinds of genes. The genes are represented by the number 1 to 10 that signify that Machine1 to Machine10 are used.

Parent1 which is represented as (1 5 2 6; 7 4 3 8; 9 10 3 5; 2 10 8 6; 1 5 9 10), illustrated in 5 rows and 4 columns. For parent2, it contains 2 rows and 4 columns as (3 9 2 8; NaN NaN NaN 5). (NaN means not a number in computing terms).

The chromosome for each parent is represented in rows. This means that the chromosomes for Parent1 are (1 5 2 6), (7 4 3 8), (9 10 3 5) and so on. One of the chromosomes from Parent1 is chosen randomly. For instance, the first row chromosome for Parent1 has been selected for the upcoming crossover function. On the other hand, the 1st row chromosome for Parent2 also is selected to be combined with the chromosome of Parent1 as shown in (Figure 5.11).

The continuous selection of the chromosomes for Parent1 and Parent2 generated 10 different Offspring after the crossover operation (Figure 11). Two Offsprings are generated from each iteration of the crossover. The Offspring1 that is created from selection and crossover with 5 chromosomes are selected for the upcoming mutation. Offspring2 is being not used because there are only 3 chromosome lesser than Offspring1.

Parent1

1	5	2	6
7	4	3	8
9	10	3	5
2	10	8	6
1	5	9	10

Parent2

3	9	2	8
NaN	NaN	NaN	5

Selection

Parent1 Selection

1	5	2	6
7	4	3	8
9	10	3	5
2	10	8	6
1	5	9	10

3	9	2	8
NaN	NaN	NaN	5

Crossover

Offspring1

3	9	2	8
7	4	3	8
9	10	3	5
2	10	8	6
1	5	9	10

Offspring2

1	5	2	6
NaN	NaN	NaN	5

Figure 5.11 Selection and Crossover

Inverting mutation takes place after the crossover. The Offspring that is generated in the previous crossover is used as the Parent again in this inverting mutation operation. Initially, a cutting point is randomly introduced anywhere along the last row of the Parent. The cutting point indicates the row of the chromosomes for the inverting mutation. The last row of the chromosome is being mutated to the initial row based on the programming code "circshift" - (mathscript function). The iterations of the row inverting mutation are replicated four times as shown in (Figure 5.12). For each offspring that is generated for row inverting mutation, three column inverting mutations takes place. For column inverting mutation, chromosome is represented column by column. The cutting point is set in the last column of the chromosome. The column based chromosome is mutated and shifted from the last column to the first column. After this, the Parent is replicated by shifting its chromosomes in columns as shown in (Figure 5.13). For each Parent that is obtained from the previous mutation step, the entire inverting mutation is expected to replicate 12 times.

3	9	2	8
7	4	3	8
9	10	3	5
2	10	8	6
1	5	9	10

Cutting Point →

Row Inverting Mutation

1	5	9	10
3	9	2	8
7	4	3	8
9	10	3	5
2	10	8	6

Figure 5.12 Row Inverting Mutation

Cutting Point ↓

1	5	9	10
3	9	2	8
7	4	3	8
9	10	3	5
2	10	8	6

Column Inverting Mutation

10	1	5	9
8	3	9	2
8	7	4	3
5	9	10	3
6	2	10	8

Figure 5.13 Column Inverting Mutation

After inverting mutation, the Child is generated and transformed to be the Parent again for deleting mutation as shown in (Figure 5.14). On completion of the previous mutation, the process of deleting mutation is simplified by just deleting the last two rows of the five chromosomes in the Child.

10	1	5	9
8	3	9	2
8	7	4	3
5	9	10	3
6	2	10	8

Deleting Mutation

10	1	5	9
8	3	9	2
8	7	4	3

Figure 5.14 Deleting Mutation

Replacement is the last step in the process of generating fractal cell layout as shown in (Figure 5.15). In fact, each fractal cell requires 10 machines where no duplicated machines or missing machines are allowed. This is because duplicated machines will increase the material travelling distance. Minimum flow distance score is the requirement for fractal cells.
As a result, machine3, machine8 and machine9 are grouped as duplicated machines that required to be replaced by missing machines. The MATLAB codes are programmed to search the missing machines. The missing machine for this scenario is machine6. Thus, machine6 replaces one of the duplicated machines.

10	1	5	9
8	3	9	2
8	7	4	3

Replacement

10	1	5	9
8	3	6	2
NaN	7	4	NaN

Figure 5.15 Replacement

The fractal cell layout that is generated after Replacement can be represented as (10 1 5 9; 8 3 6 2; NaN 7 4 NaN). From the Facility Layout Problem (FLP) that was discussed in the previous section, materials are moved into the cell through Pickup Points and moved out from the cell through Delivery Points as shown in (Figure 5.16). The Pickup Point is at (1, 1) while the delivery Point is at (3, 4).

The fractal cells are capable of processing all 15 types of product. Therefore, the materials to be produced need to be processed in specified machine routing sequence. For instance, materials that are used to produce Product1 need to be processed by machine1, machine4, machine7, machine3, machine10, and machine8 in continuous sequence. Each location of machines is represented on (x, y) coordinates. Before the materials are processed in machine1, they have to be carried into the fractal cell through Pickup Point. After processing in all the machines within the fractal cells, the final product1 gets delivered to the shipping department through Delivery Point as shown in (Figure 5.16).

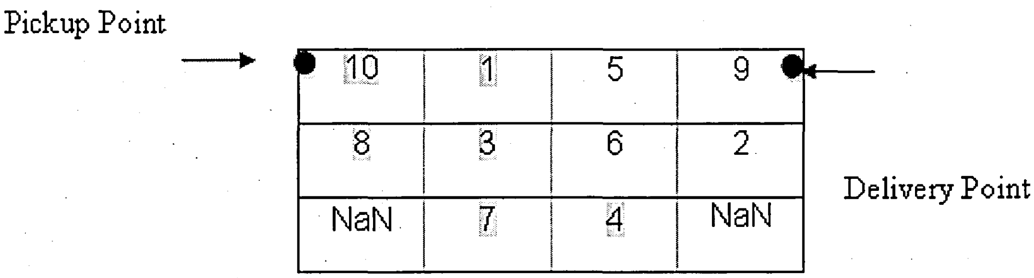

Figure 5.16 Material Routing sequence for Product1

Then the flow distance score is calculated based on the mathematical solution in MATLAB which is represented as:

Distance = abs (buffer1 (1)-buffer2 (1)) + abs (buffer1 (2)-buffer2 (2)) (5.1)

The abs is representation of absolute. The absolute value allows the distance to the left (negative value) and distance to the right (positive value) to be counted into the total distance. buffure1 and buffer2 is the matrices of data that are being stored in temporary memory.

The shortest routing distance is always considered from the various iterations that are being generated for each of the fractal cell.

5.8 Output results and discussions

The computational result of product travelling distances within fractal cells indicates the flow scores of fractal layout. Flow score is computed and represented as the product travelling distances.

The optimal fractal layout with the minimum flow distance scores is selected by MATLAB and displayed. These output data are used to draw the graphs of flow scores with different generations and flow scores with different product ranges. The GA search for an optimal solution yielded results from 100 iterations and the output is converted into the final fractal cell layout representing the fractal manufacturing layout. The material travelling distances for each of the three fractal cells work out as follows in terms of flow distance scores;

Flow distance score for Cell 1 = 205

Flow distance score for Cell 2 = 217

Flow distance score for Cell 3 = 197

Overall flow distance score for the final fractal manufacturing layout through the proposed GA = 619 and this is shown on (Figure 5.17).

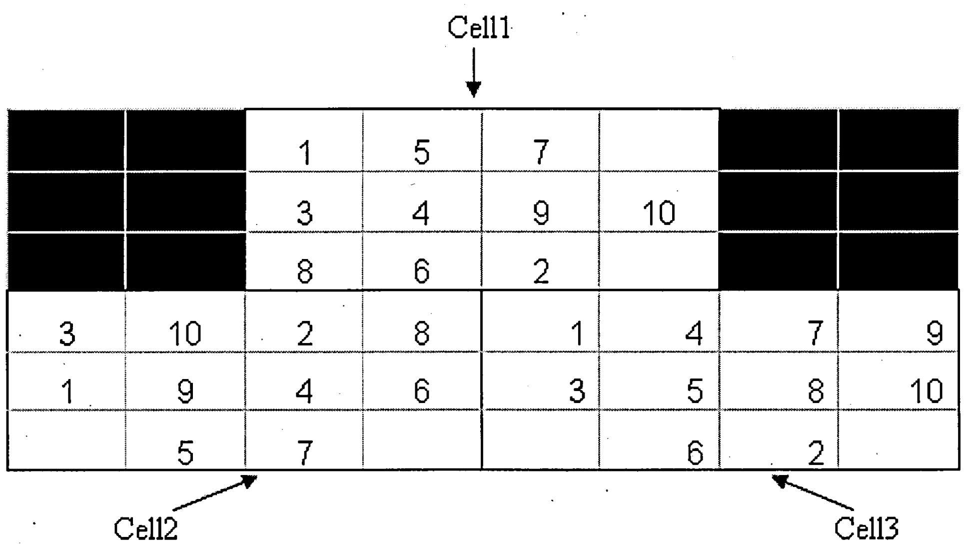

Figure 5.17 Final Fractal Manufacturing Layout A

Comparatively, the fractal layout according to (Venkatadri *et al.*1997) has machine requirements similar to our final layout requirements with the following flow distances;

Flow distance score for Cell 1 = 251

Flow distance score for Cell 2 = 252

Flow distance score for Cell 3 = 257

Overall flow distance score for Final Fractal Layout according to (Venkatadri *et al.*1997) is = 760 and that is shown on (Figure 5.18).

This shows that the flow distance score obtained from the proposed GA approach is lesser at 619 than that of (Venkatadri *et al.*1997).

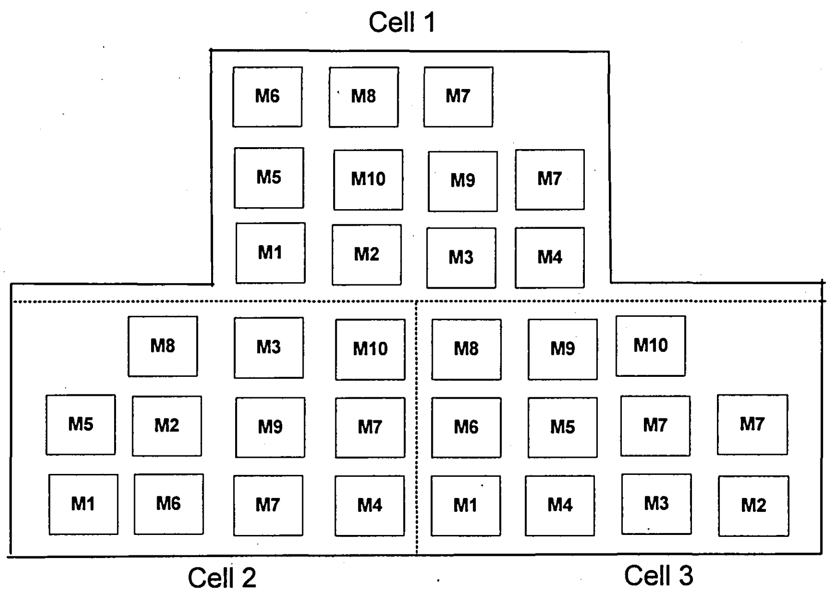

Figure 5.18 Fractal cell layout according to (Venkatadri *et al.*1997)

Ascertaining or working out the optimal number of iterations in each cell for our proposed GA approach aided in producing the right flow distances and involved plotting flow distance score against iterations as shown on figures (5.19), (5.20) and (5.21) for cells 1, 2 & 3. These plots signify the optimal flow distances at 205, 217, and 197 for cells 1, 2, & 3 respectively.

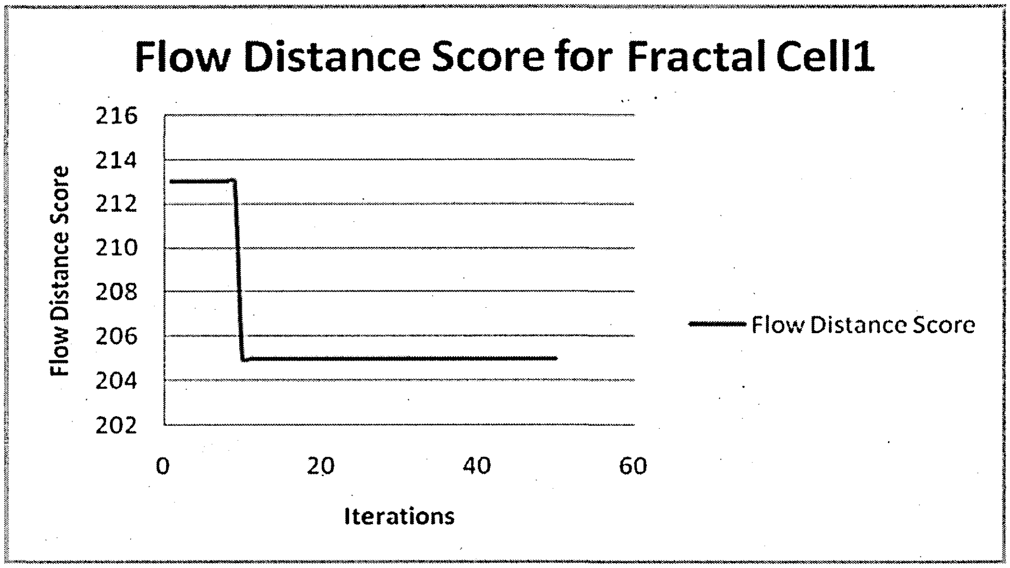

Figure 5.19 Flow distance score for fractal cell 1

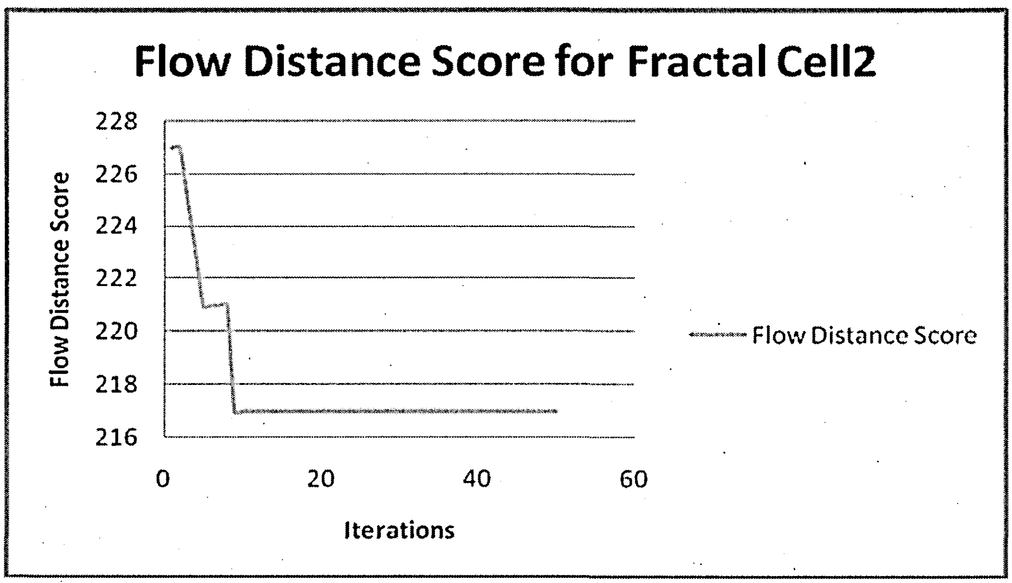

Figure 5.20 Flow distance score for fractal cell2

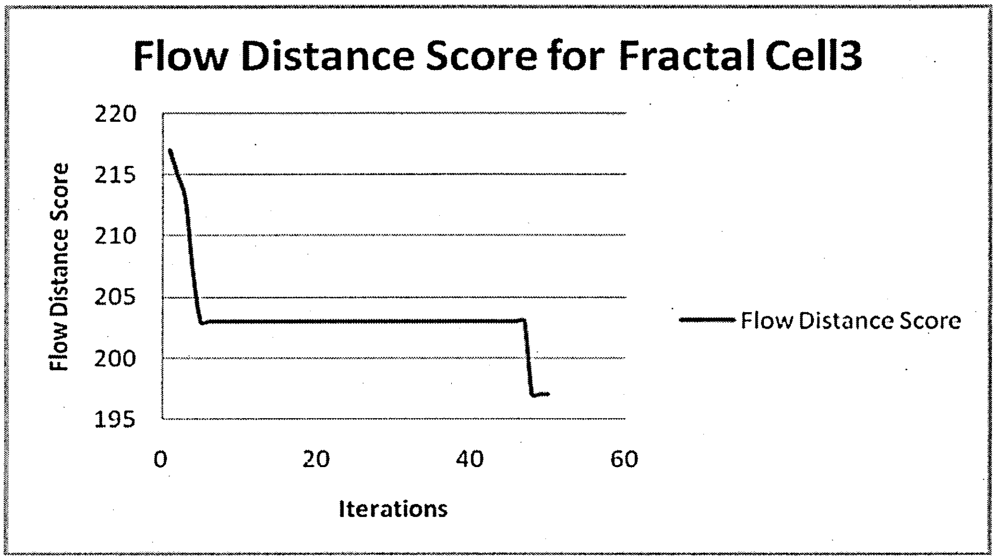

Figure 5.21 Flow distance score for fractal cell3

5.9 Conclusion

The GA approach has been applied in the design of the fractal manufacturing shop floor layout. This algorithm was used to search for the optimal fractal cell layout for efficient and effective material/ product movements within the shop floor, paying attention to capacity levels, cell composition and flow distances. This is implemented using MATLAB which handled the mathematical formulations, swapping and deleting matrices etc. quite efficiently. This work has been based wholly on the fractal job shop. The next chapter looks at the broader subject of fractal supply chain.

Chapter Six

6.0 Fractal Supply Network

The fractal internal design made in chapter five is at the core of the fractal enterprise. This dealt with fractal cell design which is at the grass root of the fractal manufacturing system. In this chapter, the fractal principle is applied in developing the Fractal supply network. Lean manufacturing system is presented, describing the origin, importance and key elemental components. The chapter progressed with the integration of lean with agility which had already been examined in chapter two, in the 'leagile' concept. Supply chain reference models are presented next looking at different examples. Finally, a brief case study of Johnson Inc. is made to illustrate the concept of 'leagilty' and the chapter is concluded.

6.1 Strategic integration of lean and agile paradigms in supply network

The quest for a synchronous supply chain is driven by advancement and complexity of the global market and the need to improve coordination of flow of resources. A total supply chain is defined as a system whose constituent parts include material suppliers, production facilities, distribution services and customers linked together via a feed forward flow of materials and feedback flow of information (Naylor *et al.* 1999; Stevens 1989). The key issues in supply chain management implementation are how to capture and manage the complexities of scenario, interdependency, process, information and cohesion in an uncertain and dynamic environment (Li *et al.* 2002; Yang and Shen 2007).

The need to involve various supply chain partners; suppliers, customers, organisations etc. proves most effective in responding to customer demands and overall supply chain management (Yang and Shen 2007). This is because it provides a harmonious environment for movement and transference of resources, while ensuring information enriched supply chain. Coordination of material, information and financial issues takes centre stage after the dynamic supply chain design process. The success in supply chain management lies in achieving harmony in raw material transformation, storage and transportation and in matching/ synchronising demand and supply in an unpredictable market environment (Michael, H., 2003). With specific emphasis on simple best practices and the appropriate use of available tools and technologies by organisations, there are frugal steps that stand them in good stead for achieving competitive advantage and market position in a supply chain. They ultimately are able to balance and manage raw materials, work in progress, component inventories, finished products and efficient allocation of scarce resources in a capricious market.

6.1.1 Lean Manufacturing System

Lean manufacturing, lean production or simply 'lean' originates from the Japanese manufacturing industry and how it revolutionized manufacturing. It is a manufacturing system that results in a better, more cost-efficient product, higher productivity, and greater customer loyalty (Womack *et al.* 1991). This strategy was focused on low labour cost through key competitive cost reduction strategy and improvement of quality through quality centers and prevention of internal defects known as Poka-Yoke (literally meaning mistake proofing) (Mahoney 1997). The concept of lean manufacturing was pioneered by Toyota after the 2nd world war, quickly ushering in an era of economic preeminence as other Japanese enterprises and businesses jumped on this remarkable band wagon (Womack *et al.* 1991). Lean as the name implies uses less of everything compared with mass production - human effort, space, investment in tools, time to develop new product and more importantly far less inventory, fewer defects and greater variety of products (Womack *et al.* 1991; Page J., 2003). The cost saving nature of lean sets the lean producer on an endless quest for perfection.

Leanness is defined as the development of a value stream to eliminate all waste, including time, and to enable a level schedule (Mason-Jones *et al.* 2000; Naylor *et al.* 1999). Level schedule means sequencing orders in a repetitive manner, and smoothing the day to day variations in total orders to correspond to long term demand (Bruce and Daly 2004). This is the prerequisite for elimination of all waste.

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- waste is undesirable - forms of waste includes; waiting, unnecessary inventory, transportation of inventory, overproduction, overprocessing, unnecessary motion, and defective units.
- the manufacturing process is linked to market requirements and,
- that the company is a continuous or uniform whole known as a value stream including customers and suppliers.

Kaizen insures 'continuous improvement' at all levels, gearing towards zero non-moving inventories, zero downtimes, zero paper, zero defects and zero delays throughout the establishment. (Womack *et al.* 1991; Page J., 2003; Xu 1994) could not agree more that the framework of lean manufacturing has basic elements which include; high efficiency manufacturing through continuous product flow, continuous improvement of processes along the entire value chain, in terms of quality and cost, and forming of multi-functional and multi-skilled teams at every level for achievement of set goals. These key elements form the backbone of the lean philosophy.

TQM is also a key important management tool for an organization, centered on quality, based on the participation of all its members and aiming at long-term success through customer satisfaction, and benefits to all members of the organization and to society (Royse *et al.*, 2006; Xu 1994). One major aim is to reduce variation from every process so that greater consistency of effort is obtained. Its main objective is sustained customer satisfaction through continuous improvement, accomplished by systematic methods for problem solving, breakthrough achievement, and sustenance of good results (standardization) (Royse *et al.*, 2006). Poka Yoke is a quality management concept developed to achieve zero defects (Womack *et al.* 1991). The three levels targeted in Poka-Yoke are; (i) elimination of spills, leaks, losses at the source or prevention of a mistake from being committed, (ii) detection of a loss or mistake as it occurs, allowing correction before it becomes a problem and (iii) detection of a loss or mistake after it has occurred, just in time before it blows up into a major issue (least effective). Another component of the Lean manufacturing system is the TPM. This management system optimizes the productivity of manufacturing equipment through systematic equipment maintenance involving employees at all levels (Royse *et al.*, 2006). Productive maintenance involves preventive maintenance, equipment reliability engineering, equipment maintainability engineering, and equipment engineering economics. TPM gives responsibility of keeping the equipment running and productive to everyone from the operator to top management. Aside from eliminating equipment downtimes, improving equipment productivity, and zeroing out defects, TPM also improves personnel effectiveness and sense of ownership, reduces operational costs and throughput times, and customer satisfaction ultimately.

6.1.2 The concept of 'Leagility'

Leanness develops a value stream by eliminating all waste and non-value added time while creating a level schedule (Mason-Jones *et al.* 2000). Two key components are identifiable/ discernible which bring about continuous improvement; these are reduction of waste and improvement of flow-fluidity. Improvement of flow exposes quality questions, and waste reduction comes as a consequence. This is achieved with use of techniques such as production levelling, pull production, the Heijunka box and improved inventory systems. This is targeted at every area and stage including customer relations, product design, supplier networks and entire factory management (Bruce and Daly 2004).

Agility as we saw in (sub-section 2.6.1) uses market knowledge and a virtual corporation to exploit profitability in a volatile market. It uses support technologies; current design and modelling techniques and tools to allow designers, production personnel and marketers to share common database of parts and products, production capacities and surrounding problems, helping them cope with variation in demand patterns and unpredictable market changes. Agile organisations promise information enriched production environment, because they share information/ data throughout the supply chain with key suppliers and distributors, forming a network of organisations or one large virtual corporation (Parkinson, S., 1999).

Leagility integrates the lean and agile manufacturing paradigms within a total supply chain by finding the optimal position for the decoupling point, (figure 6.1) to meet demand for downstream and yet provide level schedule upstream from the decoupling point (Naylor *et al.* 1999; Davis, T., 1993). Level schedule could entail sequencing orders in a repetitive pattern, and smoothing the day to day variations in total orders to correspond to long term demand. This is achieved by producing the required units in the required quantity at the required time, serving as approximation for all forms of smoothing. The combination of these two paradigms, (figure 6.1) has proved very effective in responding to the demands of a volatile market disposition.

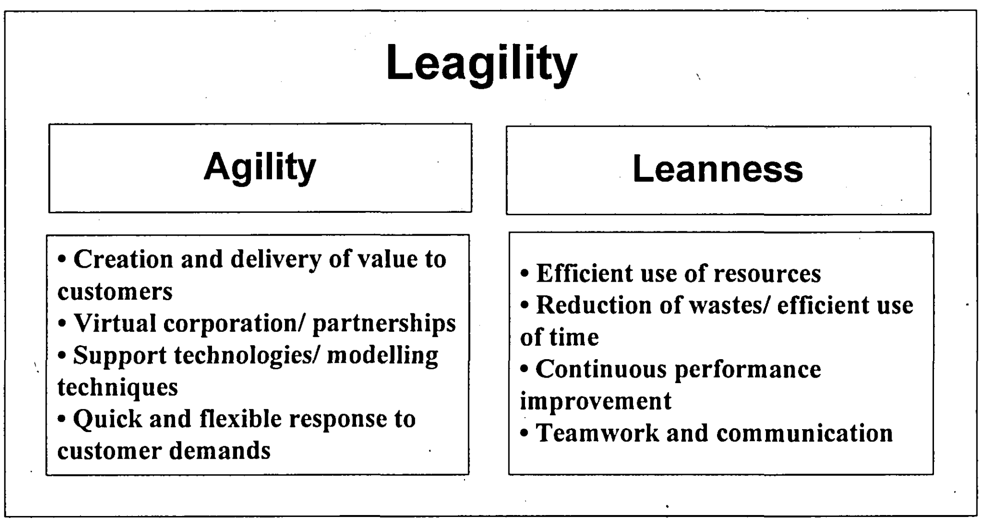


Figure 6.1 The principles of Lean and Agile paradigms

Reduction in inventory level and lead time, LT. are typical doctrines of leanness, while improvement of service to customers is associated with agility, (figure 6.2).

Lean and agile initiatives have been implemented in British Telecommunications, BT. (Robertson and Jones 1999) through creation of new customer service division, a new trend called "proactive maintenance", where an automated system carries out nightly checks of lines sending out warnings for potential faults, use of optical fibre for upgradeability and call-minders, a network based answering service. Activities upstream from the decoupling point are forecast driven and lean strategies are prominently applicable here, (figure 6.2). Demand is smooth and products flow through the value stream. However, products are pulled by customer downstream from decoupling point. Hence, agility is applied here because of high demand variability and product variety also increases per value stream.

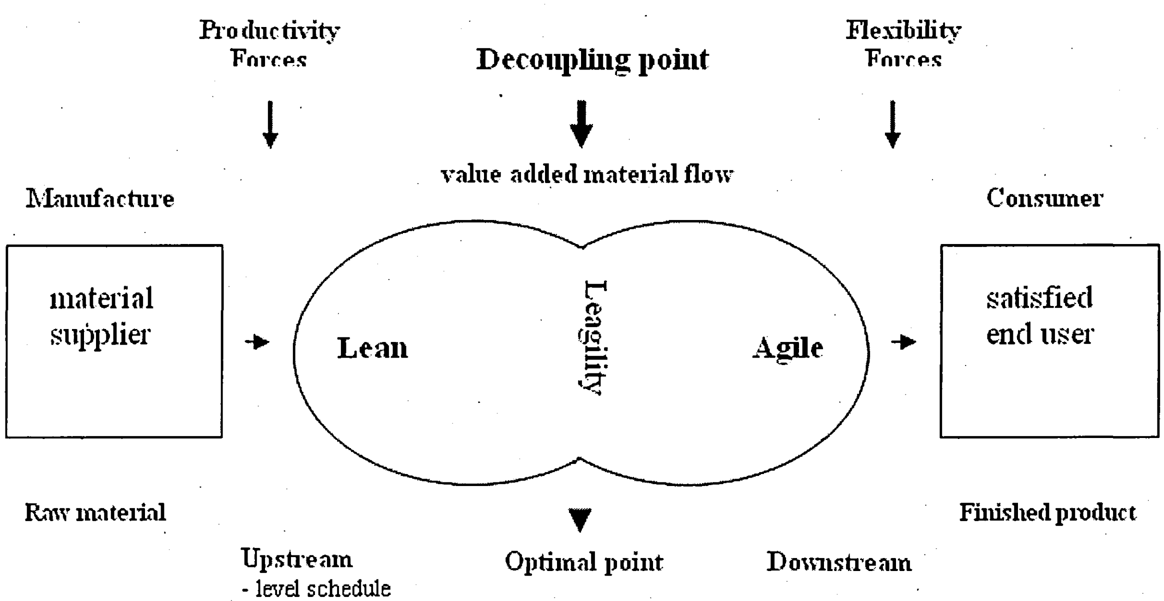


Figure 6.2 Decoupling the supply chain

The realisation of leagility depends strategically/ critically on the careful positioning of decoupling point (Saad, S., and Aririguzo, J., 2007a). It most often than not involve a trade-off between productivity and flexibility (Davis, T., 1993).

The decoupling point balances aspects of the supply chain that deal with customer satisfaction and production planning. This is done through strategic withholding of stock to buffer against variability in demand. This delayed customisation strategy is called postponement (figure 6.3). The carpet manufacturer studied in (Johnson Inc., 1990) dynamically postpones some key stages of the manufacturing process to exploit profitability.

Downstream from the decoupling point, strategic stock is held as a buffer between fluctuating customer orders and/ or product variety and smooth production output (Mason-Jones *et al.* 2000). The delayed customisation (postponement) of the product at this point enables the identification of an appropriate decoupling point (optimal point) along the supply chain. At the optimal point, the decoupling point achieves the most favourable or desirable performance; profit is maximised with minimum costs and sufficient service to guarantee customer satisfaction in a flighty market. This positioning might be dependent on the longest lead time the end customer is willing to wait for product to be delivered.

A number of factors play here prominently; product modification, process designs and organisational relationships. Postponing product differentiation reduces the risk of stock-outs and excess stock holding (Davis, T., 1993; Michael, H., 2003).

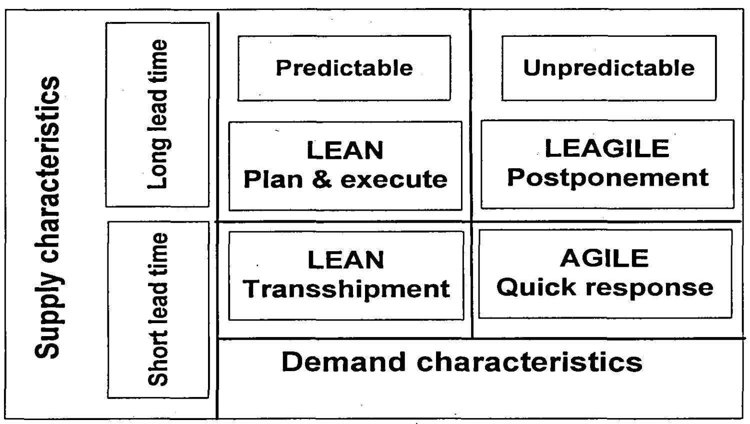


Figure 6.3 Demand vs. supply characteristics in supply chain

Textile and apparel industries in the UK. (Bruce and Daly 2004), apply quick and accurate response methods such as flexible delivery through domestic sourcing, reduced levels of stock and increased net margins in their supply chain management. This enables them respond to short product lifecycle and rapid product replenishment.

Another key inventory strategy is Transshipment (Yale *et al.* 2002). This provides secondary source of material when demand in a location turns out to be higher than expected while in a neighbouring location, excess stock is held. Transshipment leads to efficient inventory system and cost reduction by correcting associated discrepancies. It enables the sharing of stock among locations at the same echelon level, leading to a coordinated replenishment/ procurement.

The implication of not achieving the optimal point debilitates the flow of resources across the supply chain, restricting rather than enabling it.

The consequences of poor supply chain management includes poor integration of parties (suppliers and customers), fragmented processes and inappropriate performance measures.

Overall, the success in supply chain management lies in the efficient balancing of raw materials, work in progress, component inventories and finished products in response to the customer demand. Balancing of the different areas and aspects of the supply chain requires/ involves cost-service trade-offs and fine tuning of the processes to produce stability, continuous improvement, and precise optimal results desired.

6.2 Supply chain reference models

The main objective of supply chain management emphasizes delivery of value to customers through the most efficient use of resources across the chain (Saad, S., and Aririguzo, J., 2007a). The supply chain system moves products/ services and resources in physical or virtual networks from suppliers to consumers. It forms the link from the raw material, through finished product to delivery to end user.

Process reference models or reference models systematically model the ideal characteristic features of the supply chain. They integrate the well known concepts of business process re-engineering, benchmarking, and process measurement into a cross-functional framework.

The objective is achievement of end-to-end visibility into critical supply chain events and exceptions, together with the ability to proactively find the balance between supply and demand in real time. There are five unconfused stages of a process model; description of processes, framework of relationships, analysis and performance, management practices and reference model.

The supply chain council inc., SCC. (SCOR & DCOR models, 2004). developed two reference models; namely, supply chain operations reference model, SCOR. and the design chain operations reference model, DCOR. and are currently working on the customer chain operations reference model, CCOR.

6.2.1 Supply chain operations reference model, SCOR.

In the past, many exchanges in supply chain were between companies seeking to maximise their revenues, within their immediate business interests.

This reference model was developed as a cross industry standard for applying and advancing state of the art supply chain management systems and practices. It is based on five distinct management processes; planning, sourcing, production, delivery and return. It is formulated to manage and measure performance from supplier's supplier to customer's customer carefully drawing the boundaries. SCOR. proffers a data base of standard process metrics and prescriptive universal best practices for process execution (Stewart *et al.*, 1997). It spans all product transactions, customer and market interactions, but does not explicitly address issues of demand generation (sales and marketing), research and development, product development and customer support. It also contains a detailed process description, the relationship of the processes, metrics for measuring process performance, management practices and standard alignment to features and functionality. Once the process is captured in reference model form, it is implemented, described comprehensively and communicated, measured, managed and controlled, tuned and re-tuned to a specific purpose.

6.2.2 Design chain operations reference model, DCOR.

The DCOR. is formulated to provide a unique framework that links business process metrics, best practices and technology features into a unified structure to support communication and to improve the effectiveness of the extended supply chain. Much of the underlying content of the model was developed by practitioners

It is recommended to companies and organisations who are interested in applying and advancing supply chain best practices (SCOR & DCOR models, 2002). DCOR helps businesses to understand, communicate and improve their design chain. They are able to identify and benchmark their design chain processes, such as enterprise architecture analysis. The model's structure is inspired by that of SCOR. and the processes include; Planning, researching, designing, integrating, and amending. DCOR has three levels of process details; namely; The top level that has to do with different process types, configuration level that borders on different process categories and the process element level that deals with decomposition processes.

Within this level, there are four packages; gather design chain requirement, gather design chain resources, balance design chain requirements with resources and establish design chain plans. Within each level; you plan, research, design, integrate and amend.

6.2.3 Value chain operations reference model, VCOR.

The value chain specifies/ categorises the value-adding activities of a firm while maximising value and minimising costs from raw materials as input, to selling the finished product to customers. The goal is delivery of maximum value for the least possible total cost to customer. The VCOR. is a nascent model developed by the value chain group inc. (VCOR model, 2006). It offers an actual standard reference model, designed to analyse and manage the value chain in three broad excellences namely; product excellence, operations excellence, and customer excellence. These comprehensively include product development, customer relations, and supply networks. It extends the supply chain management processes to acquire, build, fulfil and support to include market, research, develop, brand, sell and support. VCOR. provides common terminology and standard process descriptions to order and understand the activities that make up the value chain. It contains fully connected inputs and outputs to and from every activity, a metric glossary, benchmarks and a collection of suggested practices. Value grid evolves from the traditional linear value chain, as a multidirectional strategy to gain influence over customer demand and create ways to manage risk and protect against fickle market conditions.

6.2.4 Global supply chain model, GSCM

This framework was introduced by the digital equipment corporation DEC., and INSIGHT Inc. for global logistics and to make the quest for visibility and control over complex supply chain processes both possible and practical. It recommends production, distribution and vendor network. Cost or weighted cumulative production and distribution times are minimised, subject to meeting estimated demand and restriction on local content etc. (VCOR model, 2006; Arntzen and Brown 1995; Michael, H., 2003). This is an elaborate model built on eight business processes managed by cross-functional teams to address different phases of the supply chain; customer relations management, customer services management, demand management, order fulfilment, manufacturing flow management, supplier relationship management, product development and commercialisation, and return management/ reverse logistics. These cross functional teams have different functional experiences and competences. They are interdependent and have overlapping interests. When managed properly, through proper collaboration, these teams provide flexibility, control and high speed networks.

6.3 Performance measurement

For continuous improvement and monitoring of quality and performance and for overall sustainability of supply chain configurations, evaluation and appraisal is imperative to determine their quality, efficiency and significance (Michael, H., 2003).

The first step in this direction is the contrivance of concise definitive set of metrics for performing the supply chain operations measurement and benchmarking. Then ways to collect and display performance data are invented, designed and elaborated. Finally, the data is used to spotlight problems and focus attention on opportunities and for strategic planning and improvement.

The supply chain measurement evaluates efficiency and responsiveness and focuses on four key aspects; customer service, internal efficiency, demand flexibility and product development. Good performance entails trade-off between cost and service. Service may be measured in the response time and fill rate, while cost may be evaluated through average landed cost and total asset etc.

6.3.1 Comparison of reference models

Apart from SCOR. and DCOR., the other reference models have different origins. However, they all have essential properties which are geared towards the same overall orientation and goals- coordination/ management of supply chain (Saad, S., and Aririguzo, J., 2007a). These properties enable supply chain designers and managers to dynamically control, configure, and adapt the chain to cope with variations in demand patterns and production mix. These models also have their strength and weaknesses.

SCOR.'s five distinct processes structure is broad ranging and touches on the entire system rather than subsections of the chain. It lends itself as a unique and powerful framework to manage and support activities and enhance communication among supply chain partners. It captures all customer interactions, product transactions including equipments, spare parts, bulk products, software etc. and market interactions. However, SCOR. does not explicitly address issues of sales and marketing, R&D, product development etc.

While SCOR. talks about sourcing, making and delivering processes, DCOR. talks about researching, designing, and integrating new products and technologies. Return or feedback is also replaced by amendment of design in DCOR.

Unlike SCOR. and DCOR., VCOR is based on three broad excellences; product, operations and customer. By configuring a VCOR. scenario, organisations can compare their value chain with other companies across multiple industries, helping them improve, quantify the benefits of implementing change, and pursue specific competitive advantage.

GSCM. is framed on eight broad business processes that span supply of raw material through to delivery of products to customer and reverse logistic. Its approach is elaborately targeted on cross-firm and cross-functional teams. However, the critical linkages are done by customer and supplier relationship managements. This has far reaching implications in addressing logistics issues of facility locations, sourcing and distribution and enterprise-wide and commodity supply base and single/ new products.

6.4 The case of Johnson Inc. - Carpet maker (Johnson Inc., 1990)

Johnson Inc. is a carpet manufacturer based in New Delhi, and prides themselves on the quality and luxury of their product. They achieve this by their flexible and robust operational approach. They have various sub-assembly plants in the USA. and elsewhere, closer to their clientele. Orders are made and created via electronic data interchange, EDI. Level schedule is also created by sequencing orders in a repetitive manner.

A key stage in carpet making is the weaving process. This involves interlacing of the yarn to form a fabric or material. The individual pieces of tufts or yarn are woven with the weft. This ensures better hold than carpet placed on pre-made backing using adhesive. Colour/ dyeing is introduced either at the raw material fibre stage or when the yarn is spun into the thickness and length suitable for the carpet in question.

The required materials and subcomponents of the products are shipped out to their sub-assembly plants and depending on the nature of the customer order, key stages of the manufacturing process are postponed to later times down stream. Final customisation is also made closer to delivery time. This leagile strategy has earned them significant reduction in lead time, LT. of nearly 33%, high quality product and lower product cost. This is because they have identified the optimal point and adjusted the decoupling point accordingly.

6.5 Conclusions

A system wide view when planning supply chain activities is a complex analytical challenge, especially when it comes to deciding how best to allocate scarce resources with so many supply chain options. Reference models have been presented which systematically integrate, coordinate and manage supply chain activities, processes and information. This results in clear visibility into events and a streamlined material flow, reducing waste and lead time. The notion of Leagility was shown as a combination of the ideas of lean and agile manufacturing paradigms in a supply chain by shifting and adjusting the decoupling point. This approach has effectively demystified the classical logistics issues of facility locations and inventory, impacting significantly on cost and cycle time.

A study of Johnson Inc. was presented to demonstrate the idea of manipulating the decoupling point along the supply chain to exploit available resources. By and large, a synchronous supply/ distribution network and effective total supply chain was shown to be achieved as a balance of various conflicting resources. The next chapter will bring careful supply chain management implementation to bear in the integration of OEMs and suppliers.

Chapter Seven

7.0 The Fractal Manufacturing Partnership (FMP)

Management of total supply chain presented in chapter six is readily apparent in this chapter. The modelling and simulation of the integration of OEMs and their key suppliers is made, maximizing lean and agile network capabilities. For a start, an elaborate discussion of partnerships and close collaborations between OEMs and suppliers is made, highlighting the advantages as well as the shortfalls. This is closely followed by the description of the system to be modelled. The chapter makes progress with the modelling of the FMP proper which is implemented using Arena. The analysis of the output performance statistics and inferences are made. Then the chapter closes with the conclusions.

7.1 Modelling the integration of OEMs and their key suppliers

Partnerships and close relationships between OEMs and key suppliers and customers are not new (Saad, S., and Aririguzo, J., 2008). OEMs increasingly outsource the manufacture of auto parts and this purchasing practice not only affect direct costs, but also impact quality, lead-time, technology, over head costs and most importantly, market success (Cross and Gordon 1995; Lewis *et al.* 1993). Many companies especially in the automotive industries rely extensively on important partnerships with key, time tested suppliers. It has been established that the cost of purchased parts and products make up to 30% to 50% of the final selling price of finished product (depending on the firm's vertical integration strategy) (Dyer *et al.* 1998; Dyer 1996; Cross and Gordon 1995). Close collaboration with suppliers from initial product design to final assembly, reduces product development time, manufacturing expense and improves quality (Noori and Lee 2000; Lewis et al. 1993). This logical and more recent progression from single sourcing has been the development of long-term supply agreements (LTSAs) between OEMs and their key suppliers. The partnership is marked by great motivation and synergism and requires cooperation, commitment, trust, teamwork and information sharing between parties and complete integration of parties involved to facilitate effective product lunches and competitive pricing (Simonian 1996; Cross and Gordon 1995). FMP is a revolutionized manufacturing method whereby OEMs go into close relationship with their key suppliers. Conceptually from the fractal system, it elevates the operation of sub-factory within a factory and enhances close links within members. This practice is necessitated by swift technological developments and by the need to take cost out of their operations. Companies examine their internal strengths, focusing their efforts towards achieving excellence in their core capabilities (Noori and Lee 2000; Dyer *et al.* 1998). These trusted suppliers then take responsibility for non-core activities. They design, manufacture, and assemble their parts on the assembly line directly to the product while sharing and co-owning the OEMs' facility. In the case of automotive companies, the OEM concentrate on the vehicle concept which includes envelop size and weight and assembly, relinquishing parts and components that have been undertaken by them in the past to trusted suppliers in a long term relationship (Cross and Gordon 1995). An increasing shift to modular component purchasing e.g. seats, belts, instruments panel and headliner may be integrated into an interior module that is undertaken by a single supplier - such as a tier-one supplier (Dorrell 1996). This results in fewer, but larger tier-one suppliers that are taking responsibility for the system design, development, assembly and management of the supply chain (Simonian 1996). OEMs need to consider which core competencies they are maintaining and which ones they will need for the future and ensure that sufficient investment in these continue. Given the long lead-term in development, failure to invest in a key area now may make it difficult later. However, de-integrating certain functions out of the organization does not have benefits for the OEM, instead capital investment requirements, operational costs and the logistical costs of maintaining product balances are all transferred to the supplier, while flexibility and the ability to concentrate on core competencies is enhanced (Cross and Gordon 1995). FMP is designed to maximize the logistical attribute of a lean production system and configured to provide strategic merging of engineering network capabilities (Phelan 1996). It combines logistical attributes of lean production methods with strategic configuration of agile network capabilities (Dyer *et al.* 1998; Phelan 1996; Noori and Lee 2000). The organizational structure of the FMP is based on series of highly coordinated production silos arranged side by side to each other to promote high degree of cooperation, communication and integration of operation and managerial activities, culminating in further reduction in work in process (WIP) inventory and instantaneous communication amongst parties involved. The communication and 'open book' information system present allows complete flexibility and an information enriched manufacturing atmosphere. There is also better service and product quality especially when suppliers feel part of the team. The degree of integration between OEM and these key suppliers is of great significance. Studies carried out by (Dyer 1996; Dyer *et al.* 1998; Lewis *et al.* 1993; and Cross and Gordon 1995) highlighted that this integration leads to improved operational effectiveness through reduced inventory, improved communication, quality, faster product development, design for manufacture and productivity. All parties must weigh the costs against the relative benefits in establishing their integration policy. Cost, control, communication, organizational climate, operations management and competitive differentiation must be analyzed exhaustively (Dyer *et al.* 1998; Cross and Gordon 1995). It is imperative to point out and highlight how OEM - supplier partnerships have evolved in recent years from an arms length relationship - just-in-time or bulk delivery, JIT (11) (Issacson 1994), through modular sequencing (Dinsdale 1996) and supplier parks (Feast 1997; Kochan 1996) to a 'hands on', proximate FMP (Friedland 1996; McElroy 1996). As the evolution progresses, there is increased responsibility on the part of the supplier for design, assembly, higher value added contribution and increased integration. However, FMP has both higher degree of integration as well as complex supplier responsibility. The focus of this paper is the determination of an optimal representation of the

FMP. This facilitates achievement of flexibility and swift response to uncertainties in the manufacturing environment, the realization of a host of other benefits as listed in (Noori and Lee 2000) and most importantly a harmonious cultural and technological integration of the parties involved in the long-term FMP relationship. However, culture integration, union philosophy that is resistant to radical changes and costs all pose a challenge in implementation of the FMP configuration. To illustrate the idea of this partnership, in the following sub-sections we look at a manufacturing environment that provides a good example to demonstrate the proposed fractal architecture.

7.1.1 System description

The system under studies is a truck assembly plant. To keep things simple, only major modular components have been represented in this model. In total there are eight sub-models that represent eight distinct operative activities. These include; Body in white, Chassis Trim supplier, Motor Engine builder, Electrical/ Electronics supplier, Motor Transmission supplier, Paint supplier/ shop, OEM (Dealership) Inspection, and the Exit logic (figure 7.1). As mentioned earlier, these suppliers have been vested with the responsibility of designing, building and assembling their modular components in close proximity to the OEM's assembly line. The suppliers rent production silos side by side to each other on the assembly line in a highly coordinated arrangement. The layout of the FMP assembly line allows complete flexibility in its operation and essentially shows the physical link with the different suppliers involved in this partnership. The OEM concerns with the brand concept which includes the envelope size and the weight of the finished truck, and is fully represented on the assembly line, eyeballing these different suppliers and supervising the overall assembly process.

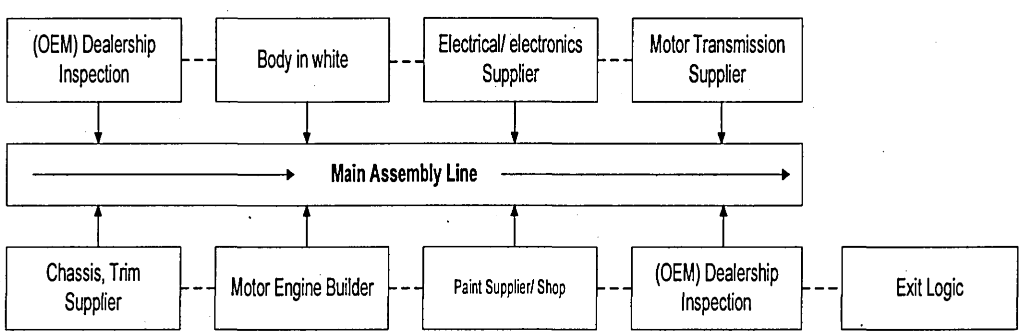


Figure 7.1 FMP assembly line (Noori and Lee 2000)

7.1.1.1 Sub-factory within factory

The FMP operates on the conceptual philosophy of the Fractal Manufacturing System (Ryu and Jung 2003 & 2004). The fractal is an independent acting corporate entity whose goals and performance can be described precisely (Warnecke 1993). The idea of 'assembly within assembly' is applicable to organizational structuring of distributed manufacturing systems (Shin *et al.* 2008). (Strauss and Hummel 1995) in their work on industrial engineering, say that a fractal is a partial system of an enterprise which offers opportunities for entrepreneurship to all employers, and it has a relation with other fractal units as a service centre. Each fractal is a customer as well as a supplier within the enterprise, and plays the role of an individual service centre within other service centre, i.e. 'a design within design' or 'pattern within pattern'. The fractal should not be confused with segments, because while the fractal evolves, navigates, organizes and administers itself, segments stay rigidly structured and work according to specified goals. Each business unit of the factory acts as an autonomous factory which is integrated within a communication network (Sihn and Von 1999). In the FMP, the suppliers are incorporated as assemblers, working within the manufacturing facility alongside the OEMs' employees. Every fractal unit has or is inherently equipped with the fractal specific characteristics. This include; self-similarity, self-organization, self optimization, goal orientation and dynamics and vitality (Warnecke 1993). These are congenital attributes of fractals.

7.1.1.2 Fractal specific characteristics

This topic has been comprehensively covered in chapter four. However, it is appropriate to show how a selection of these important attributes are represented in the FMP.

<u>Self-similarity</u>: Different units (suppliers) may arrange their internal structures differently to focus on one or more criteria, depending on their core competency (component, product, process or material). However, the units are similar in their production/ assembly function in the performance of service and pursuit of one overall corporate goal. Self-similarity is augmented by <u>self-organization</u>. This implies that fractals (suppliers in this case) have the freedom to organize and execute tasks. They may choose their own methods of problem solving including <u>self-optimization</u> that brings about process improvements. In the FMP, suppliers occupy similar, highly organized and coordinated production silos on the assembly line.

Dynamics and Vitality: Dynamics make fractals adapt to influences from the environment without formal hindrance of organization structure - a major issue in the traditional manufacturing method. Such uncertainties include delays and equipment breakdowns as will be considered during the course of this simulation. During operation, there is cooperation between fractals and a high level of individual dynamics and maximum ability to adapt to disturbances in the environment. This capability is known as vitality. Vitality is used as a record of those variables internal to the fractal that affect the environment. This is used to measure cultural, strategic, socio-informal, financial, informational and technological levels of work.

7.1.1.3 Decentralized hierarchical structure

The fractal structure is characterized by constant evolution with respect to its partners and environment (Tharumarajah *et al.* 1996). The administrative functions in the FMP are distributed over a less concentrated area, decentralizing the structure and highlighting the evolution from a vertically integrated enterprise to a network of integrated core competencies (Noori and Lee 2000). This structure is subject to a constant dynamical process of change, making them more suitable and adaptable to turbulent environment. It is also more flexible because it is susceptible to modification or adaptation and more responsive to change. Every fractal in the FMP has the same functional modules which are well-defined interfaces to the other components. In terms of job processing, this is carried out through the goal-formation process. Component relationship also exists, whereby there is a coordinative higher fractal and an active lower fractal. The fractal model manages the structural complexity and coordination of a flexible manufacturing system by maximizing local functionality and minimizing global control (Tirpak *et al.* 1992).

7.2 Modelling the FMP

The top-level model for the layout of the FMP is shown on figure 7.2. The system to be modeled is a truck assembly facility. Shots of 'body-in-white', dealership (OEM) inspection and paint shop sub-models during the simulation have been included in figures 7.3, 7.4, and 7.5 respectively. It consists of part arrivals, manufacturing cells with different machines and part departures, eight major sub-factories represented by sub-models located adjacent to each other. The suppliers design, build and assemble their modular components while residing on highly coordinated production silos. This representation not only allows flexibility and ease of organization but also shows the physical link with the participants. Transfer of parts and components is by a loop conveyor system following the concept of pre-defined entity-dependent sequences. The time between a part's arrival and that of the next part is called inter-arrival time of parts. The assembly operation starts at the 'body in white' sub-model where the metal frame arrives and within which threads and supports, doors, hoods and deck lids are assembled. On completion, this is transported by the loop conveyor to the chassis, trim supplier where seats, upholstery and windshield are coupled. After undergoing a quality check this is conveyed to the electrical and electronics supplier where the electrical aspects of the assembly operation are done, including the airbags and sensors. The motor engine builder is next on the assembly line, and he mounts the engine which was pre-built at his sub-factory. The transmission supplier follows, and here both the gear box and crank case are assembled and coupled on, followed by elaborate greasing of different movable parts. From this sub-model, nearly completed truck is conveyed to the paint shop which is manned by the paint supply who organizes the priming, initial coating and finishing of the painting. Trucks that pass the painting quality check proceeds to the Dealership (OEM) inspection. Here there is continuous eyeballing of the entire assembly progression and trucks undergo an elaborate inspection for overall envelop size and weight. There is also room for rework for trucks that don't make it through the inspection. This final inspection rolls the fully built truck off the loop conveyor and production line. All process times (the time a part spends processing in a particular cell) are triangularly distributed, inter-arrival times between successive parts arrival are exponential distributions. Load and unload times unto the loop conveyor are 2 minutes each. Information is considered from the output performance measure of 10 statistically independent and identically distributed (IID) replications, of length 480 hours, to study the system's average Work in Process (WIP) and to get statistics on the system's behavior, utilization and turnarounds. Statistics is gathered from the long run (steady state) behavior of the system, hence there is a warm-up period of 240 hours to clear the statistical accumulators

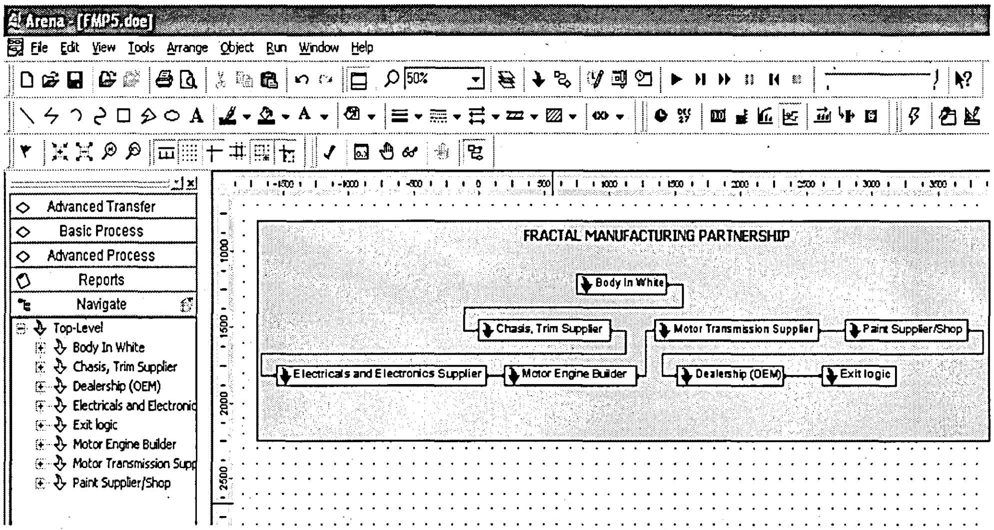


Figure 7.2 Top-level of FMP model

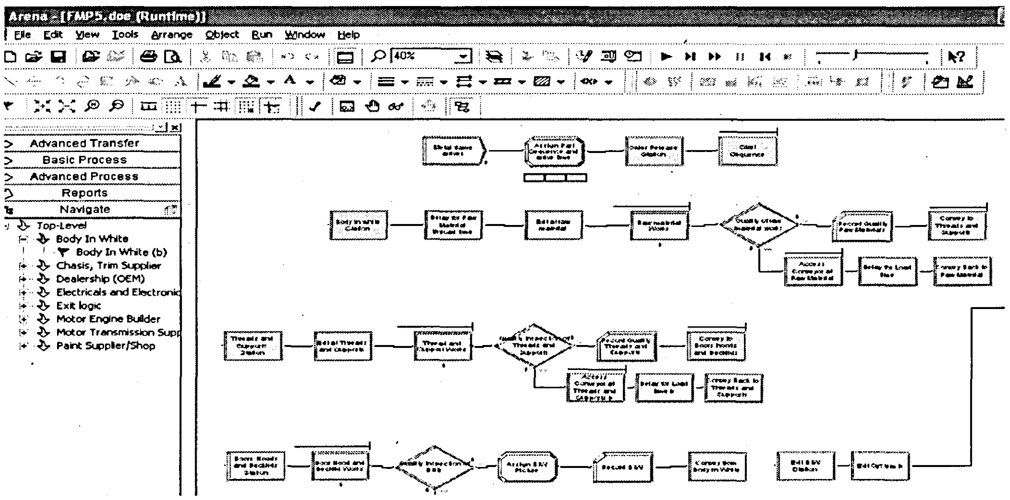


Figure 7.3 The 'Body-in-White' sub-factory

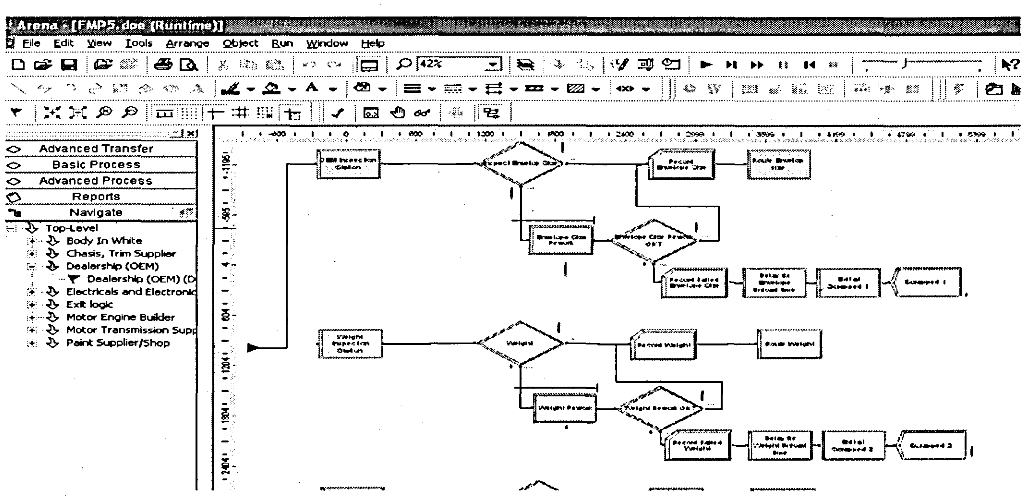


Figure 7.4 Dealership (OEM) inspections

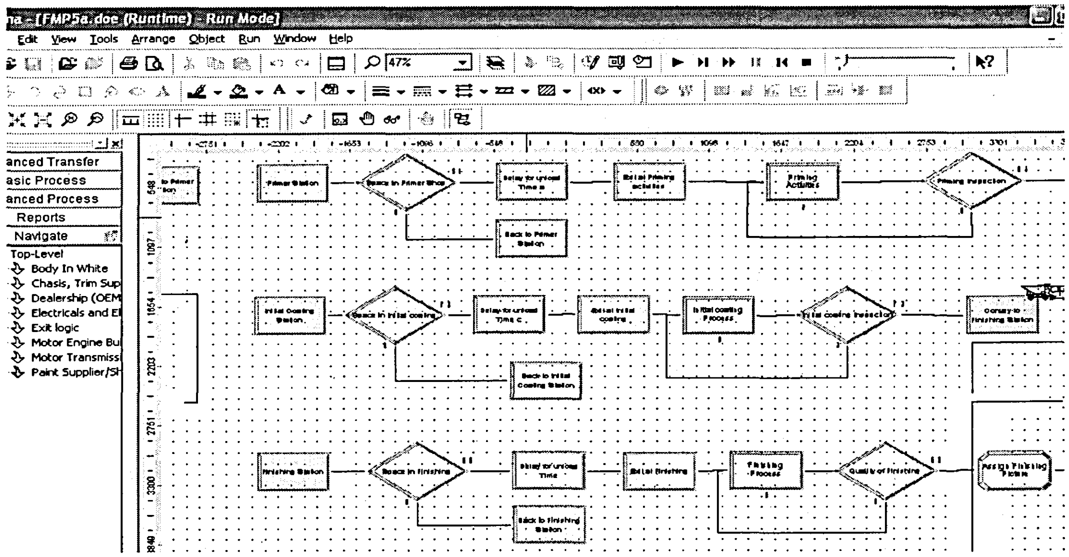


Figure 7.5 Paint Supplier/ shop sub-factory (taken at simulation time, 1243 minutes)

from biasing initial conditions. The steady state is tracked from the plot of the curve of WIP vs. Time when the effect of the empty-and-idle initial conditions appear to settle or wear out. The base time unit is in minutes. We also created an entry (Figure 7.6) labeled Total WIP in the statistic module which shows in the category overview as 'user defined', giving the time average and maximum of the total number of parts processing in the system.

	Name	Type	Expression	Report Label	Output File	Categories
1	Total WIP	Time-Persistent	EntitiesWIP(Metal Frame)+EntitiesWIP(Seat)+EntitiesWIP(Upholstery)+EntitiesWIP(	Total WIP	Total WIP History.dat	0 rows

Figure 7.6 The Total WIP Entry in the statistical data module

This signifies the compatibility of the different partners and their activities and harmony in their intra- and inter- operations. The model has taken into account the similarity requirement in organization and orientation of different sub-assemblies present. This has been built from bottom up. The sub-factories are similarly organized both internally and in their goal system. Similarity of goals means conformity of objectives in each organizational unit to the overall corporate goal (Shin *et al.* 2008; Sihn and Briel 1997).

7.3 Model verification and validation

The validity of the developed simulation model was evaluated by comparing the performance of the model to the conceptual system. The Output Analyzer provides one way of quantifying the imprecision in the parameter estimates through a 95% confidence interval. This is achieved by forming intervals with endpoints that cover the target with high probability. Half width of the output performance is the half width of a (nominal) 95% confidence interval on the expected value of the output result. These resulted in reliable and precise statistical conclusions.

7.4 Experimental design

The model of the FMP is a particularly large model, going into great depth on the lower-level modeling constructs as well as correspondingly detailed statistical requirements, comprising essentially eight sub-models as has been established. The sub-models were run separately for a start and huge amount of time was spent debugging the model and making sure that it runs without errors.

The fractal concept advocates adaptability and the ability of the system to withstand or recover from failures and uncertainties and swift responsiveness. The experiments were designed to study the effect of different factors. These variables and to what levels are as listed below. The objective is to ascertain which variables had significant effects on the performance measures. The system was investigated for robustness and responsiveness, and the performance measures were estimated for different conveyor speeds; 15ft/min, 20ft/min, 25ft/min, and 30ft/min.

The following experiments were conducted;

- Steady state (normal conditions).
  a) internal and external conditions remained unchanged
  b) no changes to number of resources (machines) in subsections
  c) no changes to input or output parameters
- Surge in demand of product.
  a) internal and external conditions were adjusted to meet increased production
  b) replicates of resources in 'body in white' (machines) became doubled to meet increased production and date requirements
  c) demand for product type was doubled or trippled throughout experiment
- Drop in demand of product.
  a) internal and external conditions are manipulated in line with reduced production
  b) minor changes in input product demand (demand for product type was halved)
  c) some resources (machines) were made redundant throughout the experiment

- Machine break-down or delay in meeting with pre-scheduled operation in a sub-factory.

  a) internal and external conditions were adjusted accordingly

  b) replicates of machines in sub-factories were made unavailable for few hours.

  c) delays were introduced in one or two sub-factories.

Within the above mentioned scenarios data was collected in each area on (i) resource utilization (ii) number in queue (iii) time in queue (iv) and cycle time (total time in system).

7.4.1 Number of replications required for experiments

To gather enough data to make the results of the experiments statistically reliable, we consider the estimation of the population mean μ of the normal distribution $N(\mu, \quad \sigma)^2$, assuming a known variance σ^2. From the population we sample n independent observations x_1 , x_2, ….., x_n yielding the sample $\bar{x}$.

Suppose we want the error of our estimate to be less than E units. Because of sample fluctuations we never can be 100% certain of achieving this goal (Kleijnen 1974). Therefore, we further specify our reliability requirement as follows. We want to be 100(1 – α)% (e.g. 95%) certain that our estimator $\bar{x}$ is not more than E units in error. Or put in an argument;

$$P(|\bar{x} - \mu| \leq E) = 1 - \alpha \tag{7.1}$$

We know that the average $\bar{x}$ of a sample of n independent value of the variate x_i , according to (Saad, S.M., 1994) satisfies,

$$P\left(|\bar{\chi} - \mu| \leq Z_{\alpha/2} \frac{\sigma(\chi)}{\sqrt{n}} \right) = 1 - \alpha \tag{7.2}$$

Then the units in error is;

$$E = Z_{\alpha/2} \frac{\sigma(\chi)}{\sqrt{n}} \tag{7.3}$$

Or the number of replications n should satisfy the following equation;

$$n = (Z_{\alpha/2} \frac{\sigma(x)}{E})^2 \qquad (7.4)$$

But since $\sigma(\chi)$ is unknown, we may decide to replace $\sigma(\chi)$ by its estimator $S(\chi)$ and correct for this estimation by the use of student's t-statistic, i.e. equation (7.2) is replaced by equation (7.5), hence we obtain;

$$P\left(\left|\bar{x} - \mu\right| \le t_{1-\alpha/2,n-1} \frac{S(x)}{\sqrt{n}}\right) = 1 - \alpha \qquad (7.5)$$

Then the solution of the equation yields;

$$n = \left(t_{1-\alpha/2,n-1} \frac{S(x)}{E}\right)^2 \qquad (7.6)$$

Or;

$$E = t_{1-\alpha/2,n-1} \frac{S(x)}{\sqrt{n}} \qquad (7.7)$$

Where: n = number of replications

E = maximum error estimate

$S(\chi)$ = unbiased estimator of the standard deviation

$t_{1-\alpha/2,\, n-1}$ = standard deviate in t-distribution

At the beginning of each run, the number of replications will be initially set to five as a pilot run to estimate the confidence limits as previously outlined in equation (7.7). The confidence interval is a statement of reliability for the estimate of the population mean and can be made as small as desired by increasing the sample size. To obtain a specific confidence interval, we use a two stage sampling procedure. The total number of replications (n*), required to reduce the error of estimation (E), to a desired value (E*), is as follows;

$$n^* = (t_{1-\alpha/2,n^*-1}\frac{S^*(x)}{E^*})^2 \qquad (7.8)$$

From equations (7.6) and (7.8), we obtain;

$$\frac{n^*}{n} = \frac{(t_{1-\alpha/2,n^*-1}\frac{S^*(x)}{E^*})^2}{(t_{1-\alpha/2,n-1}\frac{S(x)}{E})^2} \qquad (7.9)$$

Since,

$$n^* = \frac{n(t_{1-\alpha/2,n^*-1}\frac{S^*(x)}{E^*})^2}{(t_{1-\alpha/2,n-1}\frac{S(x)}{E})^2} \qquad (7.10)$$

The value of $t_{1-\alpha/2,n^*-1}$ is less than the value of $t_{1-\alpha/2,n-1}$, and also the value of S*(x) is the same as the value of S(x). Therefore, to ensure accuracy, (7.10) yields;

$$n^* \geq n(\frac{E}{E^*})^2 \qquad (7.11)$$

Where;

n* = actual number of replications needed

n = initial number of replications

E = maximum error estimate

E* = planned maximum error

E* could take values of 5 or 10 depending on the confidence interval (i.e. 95% or 90% confidence interval respectively. The results of these calculations show that different number of replications is needed for the different experiments in this simulation.

The following section provides an illustration of how to work out how many replications that is needed for different experiments:

Computing for planned maximum error, E* = 5, and initial number of replication, n = 30, from equation (7.7) and we obtain;

$$E = t_{1-\alpha/2,n-1,} \frac{S(x)}{\sqrt{n}} \quad \text{and} \quad \alpha = 5 \qquad (7.12)$$

$$E = t_{0.975,n-1} \frac{S(x)}{\sqrt{n}} \qquad (7.13)$$

$E = 13.7459$ and substituting this value for actual number of replication, n*;

$n^* \geq 30\,(\frac{13.7459}{5})^2$, hence n* ≈227 replications.

We have included n* for drop in demand and for Equipment break down below.

For **drop in demand**, and initial number of replications, n = 10;

$E = 2.26216\,\left(\frac{7.87683}{3.1623}\right)$, hence E = 5.6347 and substituting this into equation (7.11) gives;

$n^* \geq 10(\frac{5.6347}{5})^2$, and hence n* **≥13** replications

For **equipment break down**, and initial number of replications, n = 10;

$E = 2.26216\,\left(\frac{55.66727}{3.1623}\right)$, hence E = 39.82, substituting this into equation (7.11) gives;

$n^* \geq 10(\frac{39.82}{5})^2$, and hence n* **≥635** replications

From the results of the above calculations, we can infer that the proposed experiments need different number of replications.

7.5 Output statistics

The practical mechanics of making the model changes for these alternatives were managed, and that involves lots of parameter changes in the model especially the process times for different machines, under different conditions at different sub-factories. The model variants from changes in the model's input parameters were ran in an efficient and organized way using Arena Output Analyzer. The output values obtained are included in tables 7.1, 7.2, & 7.3. Overall system performance was satisfactory because the inherent dynamic nature of the system evaluates the situation on the shop floor at any given time to achieve the required responsiveness to these changes in the environment.

Table 7.1 Surge in demand

Performance measures	Conveyor velocity			
	15 Feet/m	20 Feet/m	25 Feet/m	30 Feet/m
Throughput	834	844	857	867
Cycle time	20708.75	20699.53	20679.86	20676.19
WIP	224880.80	224902.85	224889.93	224923.00
Scheduled Utilization	0.700	0.699	0.700	0.701
Wait time in queue	19909.46	19906.51	19897.09	19901.97
Number in queue	6307.01	6306.24	6308.10	6306.88

Table 7.2 Drop in demand

Performance measures	Conveyor velocity			
	15 Feet/m	20 Feet/m	25 Feet/m	30 Feet/m
Throughput	190	192	191	190
Cycle time	20832.66	20916.64	20939.78	20904.20
WIP	83981.26	83873.78	83823.29	83860.25
Scheduled Utilization	0.626	0.624	0.625	0.625
Wait time in queue	17434.44	17579.11	17587.30	17491.06
Number in queue	2194.61	2192.99	2192.35	2192.25

Table 7.3 Equipment breakdown in sub-factory

Performance measures	Conveyor velocity			
	15 Feet/m	20 Feet/m	25 Feet/m	30 Feet/m
Throughput	823	827	829	835
Cycle time	19646.98	19632.93	19639.06	19621.39
WIP	112667.61	112657.91	112642.00	112654.70
Scheduled Utilization	0.685	0.685	0.685	0.685
Wait time in queue	18578.52	18567.86	18575.01	18564.19
Number in queue	2977.84	2977.77	2977.35	2977.93

7.6 Discussions

Comparing different versions or alternatives of FMP model, there isn't huge differences in the output statistics between different replications. What makes the alternatives differ more significantly is more of a fundamental change in logic rather than simple parameter variations. In general or as a general observation, the faster the conveyor velocity, the better the throughput times (hence lead times) and machine utilization. During a surge in demand, the number of trucks produced (Figure 7.7), after 480 hour long replication, expectedly increased directly with increase in conveyor velocity and peaks at 867 trucks for conveyor velocity of 30 Feet/minutes. The system also adjusted satisfactorily and was able to adapt to new circumstances and due dates.

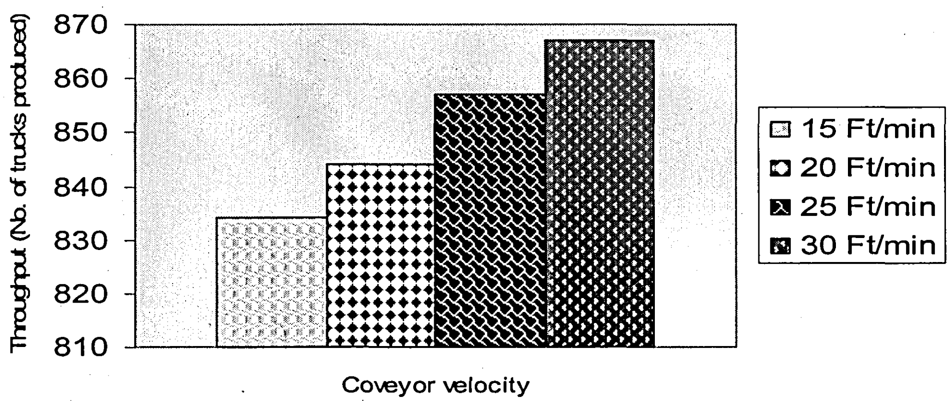


Figure 7.7 Average number of trucks produced during a surge in demand

Conversely, the average cycle time i.e. the total time parts spend servicing in system (figure 7.8) dropped with increase in conveyor velocity. The value was maximum at just above 20708 minutes at velocity, 15 Ft/min and least at about 20676 minutes.

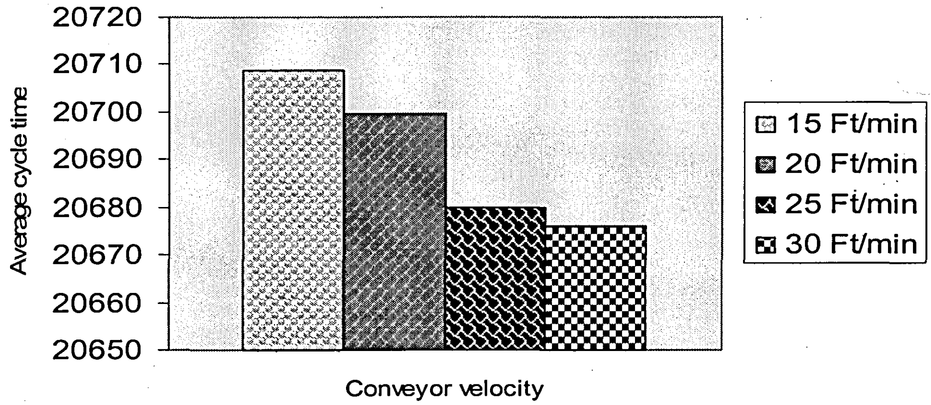


Figure 7.8 Average cycle time (in minutes) during a surge in demand

The amount of queue seen in the system during a drop in demand (Figure 7.9) dropped with increase in conveyor velocity. The system coped quite fairly with at least 2192 parts at velocity of 30 Ft/min. Expectedly, the system was not exploding with parts in service since there weren't too much activities going on.

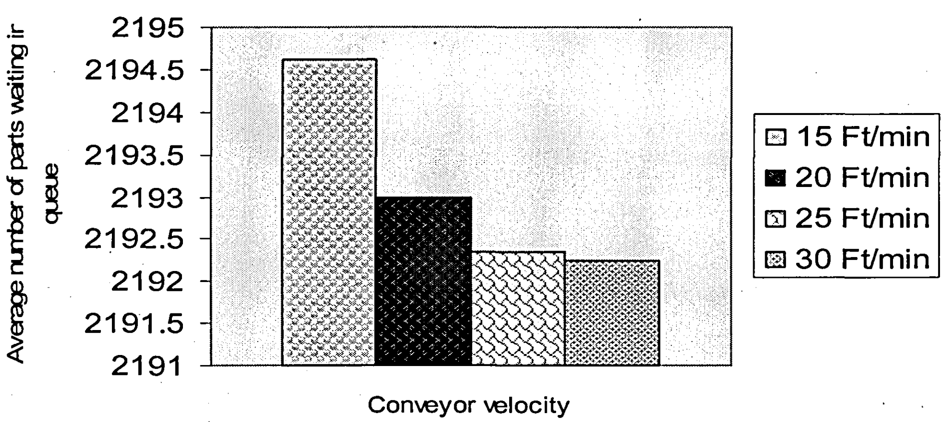


Figure 7.9 Average number of parts waiting in queue during a drop in demand

The system's behavior was investigated during some five hour equipment breakdown in two sub-factories. It was observed that the system carried on operating, utilizing hidden capability of other resources (machines). The average scheduled utilization during equipment break down (figure 7.10) stayed marginally displaced at just under 69% throughout, not minding an increase in conveyor velocity.

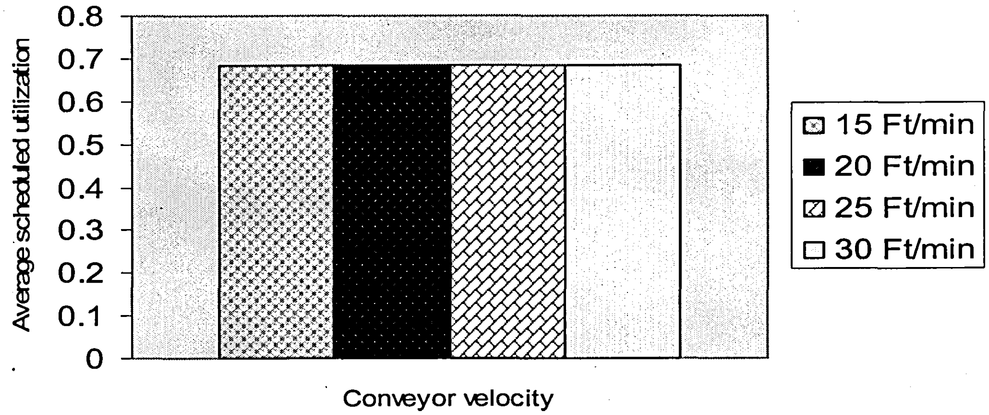


Figure 7.10 Average scheduled utilization during equipment breakdown

7.8 Conclusion

This chapter has reported on the simulation model development of the integration of automotive OEM and their key suppliers. The modeling and simulation focus was on harmonizing as well as synchronizing the operations of these different parts suppliers, who have now become assemblers of their modular components while residing side by side with each other on the assembly line, and harnessing the synergic effects of such 'hands on' collaboration to boost lean production and provide agile capability for rapid response to competitive markets. The Fractal Manufacturing Partnership has remarkably improved relationship between OEM and their key suppliers in part and tremendously impacted on the way goods are manufactured. Among other key advantages of this collaboration include;

- The synergy in the partnership is formidable, with the pool of suppliers integrating product design and production planning to enhance operational communication.
- There is improved design for manufacture, since the supplier is directly responsible for design and assembly of their modular component.
- Inventory is drastically reduced, improving leaner manufacturing capabilities and making room for less emphasis on fire fighting.
- There is also improved communication, as there is information enriched environment due to the inherent open-book relationship, leading to faster product development and high responsiveness.

- The collaboration also encourages more investment in Research and Development, improving the quality of the product.
- There is reduction in bureaucracy and excessive management as this web of experts (suppliers) are given charge of their different operations.

However, the partnership is not without some downside. The drawbacks in the relationship include the following;

- Culture integration is a big deal and cohesion of these different suppliers who have come to reside side-by-side under one roof from different backgrounds.
- Union philosophies, resisting some of the radical changes and costs in the new collaboration.
- Trust issues in what is suppose to be an open-book relationship.

By and large, the truly agile manufacturing framework/ structure formed in the FMP is ultimately used to carry out production with a sense of shared or mutual dependency, motivation and a heightened sense of responsibility between OEMs and this web of suppliers that provide all the elements required in the production process perhaps under one roof.
The next chapter forms a supplier selection framework for the selection of quality and reliable suppliers prior to going into the partnership.

Chapter Eight

8.0 Supplier Selection in FMP

The success and realization of the FMP modelled in the last chapter (chapter seven) hinge critically on quality and reliable suppliers. Selection of tried and tested suppliers to go into the FMP is made in this chapter. This is carried out using the Analytical Hierarchy Process (AHP) approach. The supplier selection process is defined and described for a start. Then the buyer - supplier relationship is differentiated from OEM - supplier alliances. The analytical hierarchy process is then presented, making the mathematical formulations and assumptions. Modelling the supplier selection using the AHP is carried out and implemented using MATLAB. The model results and discussions are made. The chapter is then concluded.

8.1 Analytical Hierarchy Process Approach to supplier selection issues of FMP

The vigorous competition in today's global market, sweeping changes in technological advancement, introduction of products with short life cycles and the heightened expectations of customers have drawn attention on supply chains (Chan 2003). Growing competition in manufacturing and management has made frugal resource management ever more relevant in recent times (Akinc 1993). Manufacturers tend to manage their suppliers in different ways leading to supplier development, supplier evaluation, supplier selection, supplier association, supplier coordination etc. (Chan 2003; Boer *et al.* 2001). There has been increased emphasis on alliances, collaborations and networks particularly between Original Equipment Manufacturers (OEMs) and their key suppliers to achieve competitive advantage especially in the face of global volatile and unpredictable markets (Noori and Lee 2000). Involving suppliers from initial product development through to final assembly reduces product development time, manufacturing expenses and improves quality (Noori and Lee 2000). OEMs are increasingly handing over their non-core business to key suppliers who can demonstrate the expertise and capability necessary for the task. These key suppliers are responsible for designing, making and assembling their modular components on the assembly line, while co-owning the OEM's facility. Reduced lead times, operational costs and inventory, shorter product life cycle and improved product quality, and less emphasis on fire fighting have been reported as some of the advantages of this nascent manufacturing formula. In FMP, OEMs will focus on their core capabilities (as we saw in chapter 7) which include specification of envelop size and weight and overall supervision of the production process while handing over non-core business to key suppliers who can demonstrate the expertise and capability necessary. It provides the synergy and motivation required to form leaner core business units interacting to create mass customised products (Noori and Lee 2000). Selection of the right set of suppliers is of strategic importance in forming this alliance and could help or hinder the inherent strength in the collaboration. Therefore, comprehensive framework is needed to facilitate the decision making in the supplier selection process and to cope with the supplier integration trends of various manufacturing strategies (Noori and Lee 2000; Şen *et al.,* 2007). However, selecting the right suppliers is always difficult and complicated due to incomplete information, subjective and imprecise preference and vast qualitative criteria needing to be considered. The traditional approach to supplier selection has been to maintain a competitive supplier base, keeping suppliers at arm's length, and playing them off against each other to achieve the least invoice cost (Akinc 1993; Boer *et al.*

2001). However, least invoice cannot be the sole basis for selection when implicit or explicit quality, delivery reliability, lot size, paper work, returns, transportation and expediting costs are all being considered (Akinc 1993).

Various mathematical framework and system modelling have been developed and proposed by researchers to support supplier selection problems in various applications (Chan *et al.*, 2007; Şen *et al.*, 2007; Chan 2003; Şevkli *et al.*, 2008; Sevkli *et al.*, 2006; Ramanathan 2006; Selçuk 2006; Ting *et al.*, 2008; Tam *et al.*, 2001). It has to be said that most of the supplier selection methods are based on procurement situations and buyer-supplier relationships. None has ventured explicitly into the FMP or the OEM/ supplier collaboration. It is also worthy of note that selecting a small number of vendors to have long term close relationships is an important step and urgent JIT requirement (Akinc 1993). The model proposed in this chapter is simple, systematic, logical and mathematical to guide user OEMs in making robust and informed decision in the supplier selection task.

8.2 Supplier selection process

The automotive industry, consumer and industrial electronics, appliances, and machine tools are some examples of industries where companies tend to depend on outside sources for a large number of materials/ parts, making up a significant part of their cost of goods sold (Akinc 1993). One of the big steps in the process of supplier selection is the formulation of criteria (Sen *et al.* 2008). Many researchers have approached the subject of supplier criteria in different ways and have emphasized this importance (Min 1994, Barbarosoglu and Yazgac 1997, Krause and Ellram 1997, Ghodsypour and O'Brien 1998, Masella and Rangone 2000, Boer *et al.* 2001, Humphreys *et al.* 2001, Liu and Hai 2005). The work by (Sen *et al.* 2008) is particularly significant and relevant to the FMP because it not only investigates two basic possible qualitative and quantitative criteria, but most importantly, their approach could assist decision makers in determining the OEM-supplier integration level. This is vital in the long-term relationship inherent in the FMP. Quantitative criterion measures concrete quantitative dimensions such as cost where as qualitative criterion deals with quality of design. Trade-offs are usually required to resolve conflicting factors between the two criteria (Sen *et al.* 2008). Other important approaches applied to the supplier-related problems are outranking method (Boer *et al.* 1998); discrete choice analysis (DCA) (Verman and Pullman 1998); theory testing (Ragatz *et al.* 1997; Dowlatshali 2000; Shin *et al.* 2000), problem definition and criteria selection (Min 1993; Mandal and Deshmukh 1994) and Analytical Hierarchy Process (AHP) (Rebstock and Kaula 1996; Babic and Plazibat 1998; Masella and Rangone 2000), multiple phases in supplier selection (Vokurka *et al.* 1996), categorical methods in pre-qualification of suitable suppliers (Zenz 1981; Timmerman 1986), Data envelope Analysis (DEA) (Weber and Ellram 1992; Weber and Desai 1996; and Weber *et al.* 1998; Papagapiou *et al.* 1996), Cluster analysis (CA) (Hinkle *et al.* 1969; Holt 1998), Ng *et al.* (1995) worked on case-based reasoning (CBR) systems for-prequalification of suppliers, and linear weighting models by (Zenz 1981; Timmerman 1986). These methods lay emphasis on the importance of the formulation in the buyer-supplier context. The set of criteria understandably shifts significantly or considerably when it comes to the OEM-supplier alliance since it advocates a more permanent, long-term relationship. Dickson (1966) identified and published 23 criteria that are considered in various supplier selection problems. His work is important in this context. In an extensive literature review by (Sen *et al.* 2008), 49 supplier selection criteria are seen as important in considering which supplier to select, but again these are within the buyer- supplier or procurement context. The purpose of this work is to highlight a systematic procedure to create a framework among identified and existing criteria, which of these are relevant and effective when OEMs select suppliers to co-own their facility in the FMP.

8.3 Buyer - Supplier vs. OEM - Supplier integration strategies

Determining the buyer-supplier level of integration is the most important decision in the buyer-supplier selection process (Masella and Rangone 1995). Likewise, the level of integration and closeness between manufacturers and suppliers in the FMP is of vital importance in the supplier selection process. Two well known types of relationships between buyers and suppliers are identified as 'adversarial competitive' and collaborative partnership' (Imric and Morris 1992; Gules and Burgess 1996; Humphreys *et al.* 2003). Tough negotiation, focus on price, short-term contracts and multiple sourcing all fall under the adversarial model (Matthysseus and Van den Bult 1994), while the collaborative model places more emphasis on suppliers' competence in production, distribution and post-purchase service. The FMP leans strongly towards a collaborative association based on cooperation, mutual benefit and trust and relational exchange, which all come from the collaborative partnership. The ability of the supplier to have access to the business skills and expertise of their buyer partners is also note worthy (Imric and Morris 1992), which attribute the FMP advocates while sustaining an information enriched , 'open book' approach. The degree of buyer-supplier relationship styles have been looked at closely by different researchers and can be categorised into five levels (Chan 2003; Perona and Saccani 2004; Ghodsypour and O'Brien 1998) based on effect of interaction (long lasting, cyclical and temporary) and value of the interaction depends on product, process, human resources and technology. These five levels of relationships are temporary basic relationship, temporary operational relationship, cyclical operational relationship, long lasting strategic relationship (Şen *et al.* 2007). The FMP conforms to level five category, where business partnership and integration is desired. The OEM fully interacts or cooperates with the suppliers in the long term. FMP is based on series of production silos arranged serially and highly coordinated with one another (Noori and Lee 2000). The suppliers are directly involved in the manufacturing process rather than supply and leave. High level of technology facilitates both OEM and suppliers to work towards the same strategic goals. This alliance warrants sharing of business related information to explore new markets with novel ideas and technologies. It also encourages more investment in R&D. It is note worthy the different degrees of integration and how OEM-supplier integration has evolved from JIT, JIT11, modular sequencing, supplier parks to FMP (Noori and Lee 2000). The OEM- supplier integration levels is of crucial importance especially in the criteria definition phase. (Chan 2003) noted that manufacturing capability and performance history criteria are very important factors when it comes to management capability and financial performance.

8.4 Framework for defining the supplier selection criteria

8.4.1 AHP modelling procedure

The AHP was originally designed and applied by (Saaty 1980; Saaty 2008; Saaty and Vargas 1991; Saaty and Vargas 2000) for solving complex multiple criteria problems involving comparison of decision elements which are difficult to quantify. It considers both qualitative and quantitative criteria in a hierarchical structure (ranking) for supplier selection (Ting and Cho 2008). The AHP divides a complex decision problem into a hierarchical algorithm of decision elements. A pair wise comparison in each cluster (as a matrix) follows, and a normalized principal eigenvector is calculated for the priority vector which provides a weighted value of each element (Tin and Cho 2008) within the cluster or level of the hierarchy and also a consistency ratio (used for checking the consistency of the data). The main theme is the decomposition by hierarchies as shown in (figure 8.1). Rao (2006) finds that AHP is based on three basic principles, namely; decomposition, comparative judgments, and hierarchical composition of priority. The decomposition level breaks down complex and unstructured criteria into a hierarchy of clusters. The principle of comparative judgments is applied to construct pair wise comparison of all combinations of the elements in a cluster with respect to the parent of that cluster. The principle of hierarchical composition or synthesis is applied to multiply the local priorities of elements in a cluster by the 'global' priority of the parent, producing global priorities throughout the hierarchy.

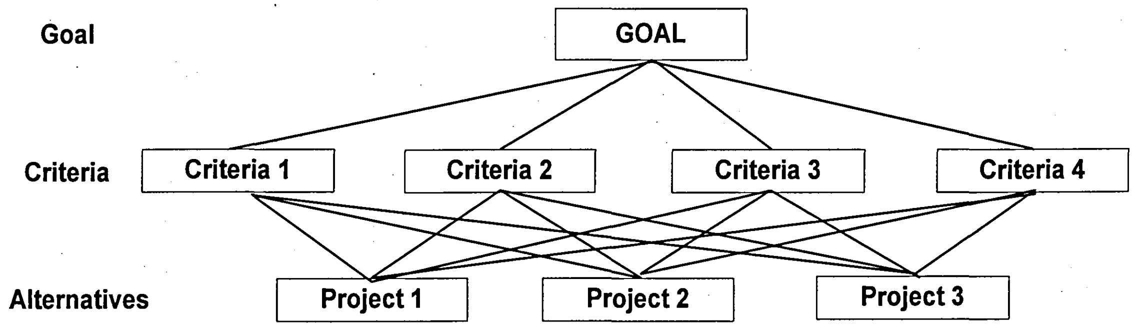


Figure 8.1 General structure of hierarchy of AHP (Chan 2003)

8.4.2 Mathematical formulation leading to supplier selection

Based on the AHP approach, weights of criteria and score of alternatives are called local priorities which are considered as the second step of the decision process (Sevkli *et. al.* 2006). The decision making process requires preferred pair-wise comparison concerning weights and scores. The value of weights v_i and the scores r_{ij} are extracted from the comparison and listed in a decision table. The last step of the AHP aggregates the local priorities from the decision table by a weighted sum of the type;

$$R_j = \sum_i v_i \times r_{ij} \qquad (8.1)$$

R_j represents the global priorities and is thus obtained for ranking and selection of the best alternatives. Assessment of local priorities based on pair-wise comparison is the main constituent of this method where two elements E_i and E_j at the same level of hierarchy are compared to provide a numerical ratio a_{ij} of their importance. If E_i is preferred to E_j then $a_{ij} >$ 1. On the other hand the reciprocal property, $a_{ji} = 1/a_{ij}$, j = 1,2,3,4,….,n and i = 1,2,3...n always holds. Each set of comparison with n elements requires [n x (n - 1)] /2 judgments (Sevkli *et al.* 2006). The rest half of the comparison matrix is the reciprocals of those judgments lying above the diagonal and are omitted. The judgments are made based on a 9-point ratio scale (Table 8.1) that ranges from 2 factors being equally important to 1 of the factors being absolutely more important than the other.

The decision maker's judgments a_{ij} are usually estimations of the exact. Hence, a consistency ratio method was introduced by (Saaty 1980) to govern the consistency of judgments. If a decision maker states that criterion x is of equal importance to criterion y, then, $a_{xy} = a_{yx} = 1$, and if criterion y is extremely more important than criterion z, then, $a_{yz} = 9$, & $a_{zy} = 1/9$, then criterion z should be having the same weight to criterion z as criterion y does. However, the decision maker is often unable to express the consistency of the judgment and this could affect the analysis. Hence, Saaty's consistency method measures the inconsistency of the pair-wise comparison matrix and sets a threshold boundary which should not be exceeded. In the non-consistent case the comparison matrix A may be considered as a perturbation of the previous consistent case. When the entries a_{ij} changes only slightly, the Eigen values change in a similar fashion. The consistency index (CI) is calculated as follows;

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8.2}$$

where n is number of comparison elements.

Then, the consistence ratio (CR) is calculated as the ratio of consistency index and random consistency index (RI). (RI) is the random index representing the consistency of a randomly generated pair-wise comparison matrix.

n	1	2	3	4	5	6	7	8	9	>9
RCI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.45

Table 8.1 Random consistency indices for different number of criteria (n)

the consistency ratio (CR) is calculated as follows;

$$CR(A) = \frac{CI(A)}{RCI(n)} \tag{8.3}$$

If CR(A) < 0.1 (10%), the pair-wise comparison matrix is considered to be consistent enough. In the case where CR(A) > 0.1, the comparison matrix should be improved. The value of (RI) depends on the number of criteria being compared or considered.

8.5 Modelling the FMP supplier selection process

8.5.1 Modelling procedure

The model sorts the decision problem in a hierarchical system of decision elements as shown on (figure 8.2). Pair-wise comparison matrix of these elements is constructed, normalised principle Eigen vector is calculated for the priority vector which provides the measurement of weights (relative importance) of each element. The general procedure of the model is summarised below;

(i) Construct the hierarchy system, including several independent elements. The model has four levels - the overall goal, main evaluation criteria, sub-criteria and alternatives.

(ii) Pair-wise comparison of criteria and alternatives is then carried out, finding the comparative weights amongst the attribute decision elements. The mathematical modelling utilizes the 'slider' function of MATLAB GUI (Graphical User Interface) as comparative input tool. The quantified subjective decisions are stored in allocated cells. The outcome is a ranked priority order of criteria and ranked priority order of decision alternatives under each criterion.

(iii) Calculate the weights and test the consistency and calculate the Eigen vector of each comparison matrix to obtain the priority of each decision elements. Hence, for each pair-wise comparison matrix, the Eigen value of the matrix λ_{max} and Eigen vector w (w_1, $w_2 \ldots w_n$), weights of the criteria is estimated.

(iv) The last step in the modelling is finding the overall priorities for decision alternatives. This is calculated by multiplying the priority for each alternative under each criterion by the weight of each criterion (local weights). The calculations is performed from the lower level to the higher level of hierarchy where the outcome of the step is ranked in order of the decision alternatives to aid the decision making process.

(V) Validation of the model is needed to test the logical and mathematical correctness and reliability of the model. To this end, the result from the case study by (Sevkli *et al.* 2006) is imported into the project. The (Sevkli *et al.* 2006) work uses Data Envelopment Analysis (DEA) approach and this is embedded into the analytic hierarchy process methodology. The criteria, sub-criteria, and alternatives and the scores of the comparisons are used as they are. The final outcome of the mathematical model is compared with these (Table 8.2).

	Sevkli *et al.* 2006	Outcome of model
Supplier 1	0.379	0.37925
Supplier 2	0.365	0.36787
Supplier 3	0.256	0.25287

Table 8.2 Comparison with Sevkli *et al.* 2006

A look at (table 8.2) shows that the model closely compares to the results from that of (Sevkli *et al.* 2006) and is validated to 0.07%. The error is very small and hence negligible, showing logical and mathematical correctness and so the model can be used for the FMP experimentation.

8.5.2 FMP Supplier Criteria

Supplier selection criteria, sub-criteria and alternatives for the FMP have been formed based on relevant extensive literature (Ting *et al.* 2008; Sevkli *et al.* 2006; Sevkli *et al.* 2008; Chan, 2003; Selçuk, 2006; Şen *et al.* 2007; Chan *et al.* 2007) reviewed and consulted for the project. These are considered while creating optimal supplier selection criteria for the FMP. They are grouped as either tangible or intangible depending on how perceptible or realistic they are. They form the framework on (figure 8.2), and include the following; business criteria, manufacturing, quality assessment, performance assessment, organisational culture and strategy, personnel management, compatibility and information technology. The first four are considered tangible while the rest are intangible criteria.

Overall Goal | Main Criteria Level 1 | Sub-criteria Level 2

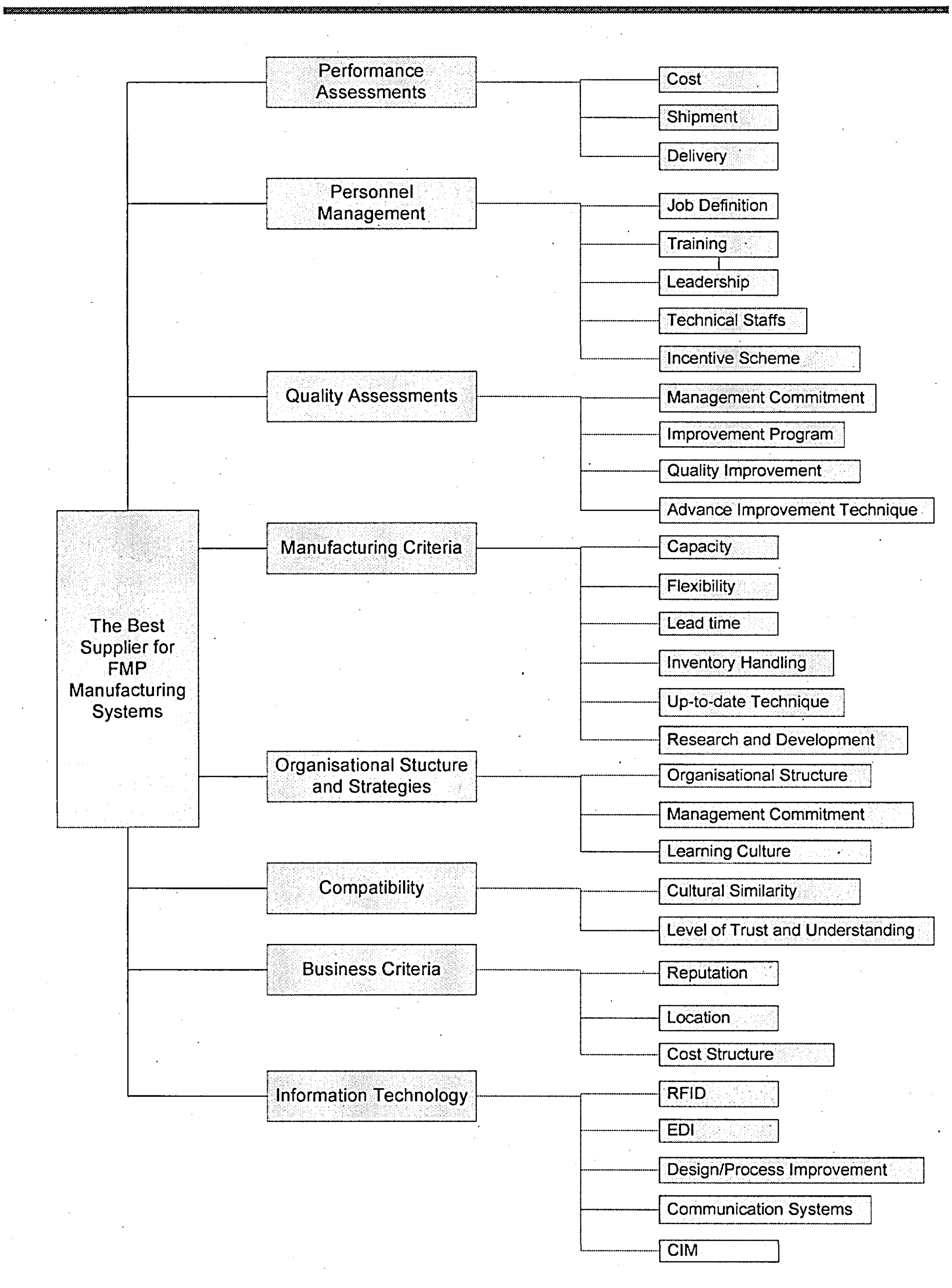


Figure 8.2 Framework of the supplier selection process

8.6 MATLAB AHP model

The MATLAB AHP model forms key component of the supplier selection process as the model supports and extends the main purpose of the project. This is built using MATLAB R2008a version 7.6.0.324 because this version is compatible to run the codes which otherwise can not run the 'table' function of Graphical User Interface (GUI). MATLAB programming language is preferred because the AHP model is mainly mathematical and utilises large amounts of matrices and matrix calculations. Its high-performance language for technical computing integrates computation, visualization, and programming and essentially expresses the problems and solutions in mathematical notation.

The model is designed to fetch input of pair-wise comparison data of different criterion and alternatives and process these data to an output of optimum score of the alternatives. Hence, the GUI is used for this particular model design to create a user-friendly interface. The GUI comprises 5 different model sections easily selectable by push buttons on the panel displaying the different hierarchy of the AHP model (Figure 8.3). It is designed to receive

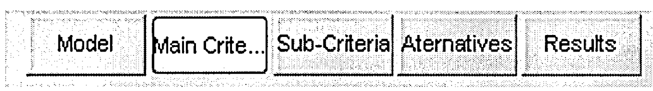


Figure 8.3 The five model sections

comparison input using slide bar mechanism. Two separate list box contain the comparative elements of the model. The scale of the slider is designed to a range of 1-9 as described earlier. Hence, users could compare the desired elements by selecting a criterion and this would be displayed at the edge of the slide bar (Figure 8.4). Dragging the slide bar towards 'Performance Assessments' (blue) means it is more important than 'Personnel Management' (Red) and vice versa. The input of each element is recorded in a tabular form and the AHP output is calculated once the relevant data is collected and the consistency ratio is calculated along with the AHP weights. (Figure 8.4) to (Figure 8.6) illustrate the input of the model where each relevant elements of the model is compared quantitatively and the result is recorded for final calculations. (Figure 8.7) and (Figure 8.8) display the final result in a bar chart with respective scores indicated. These results can be exported to Microsoft Excel files for reference purposes using the 'Load' and 'Save' buttons on the model panel.

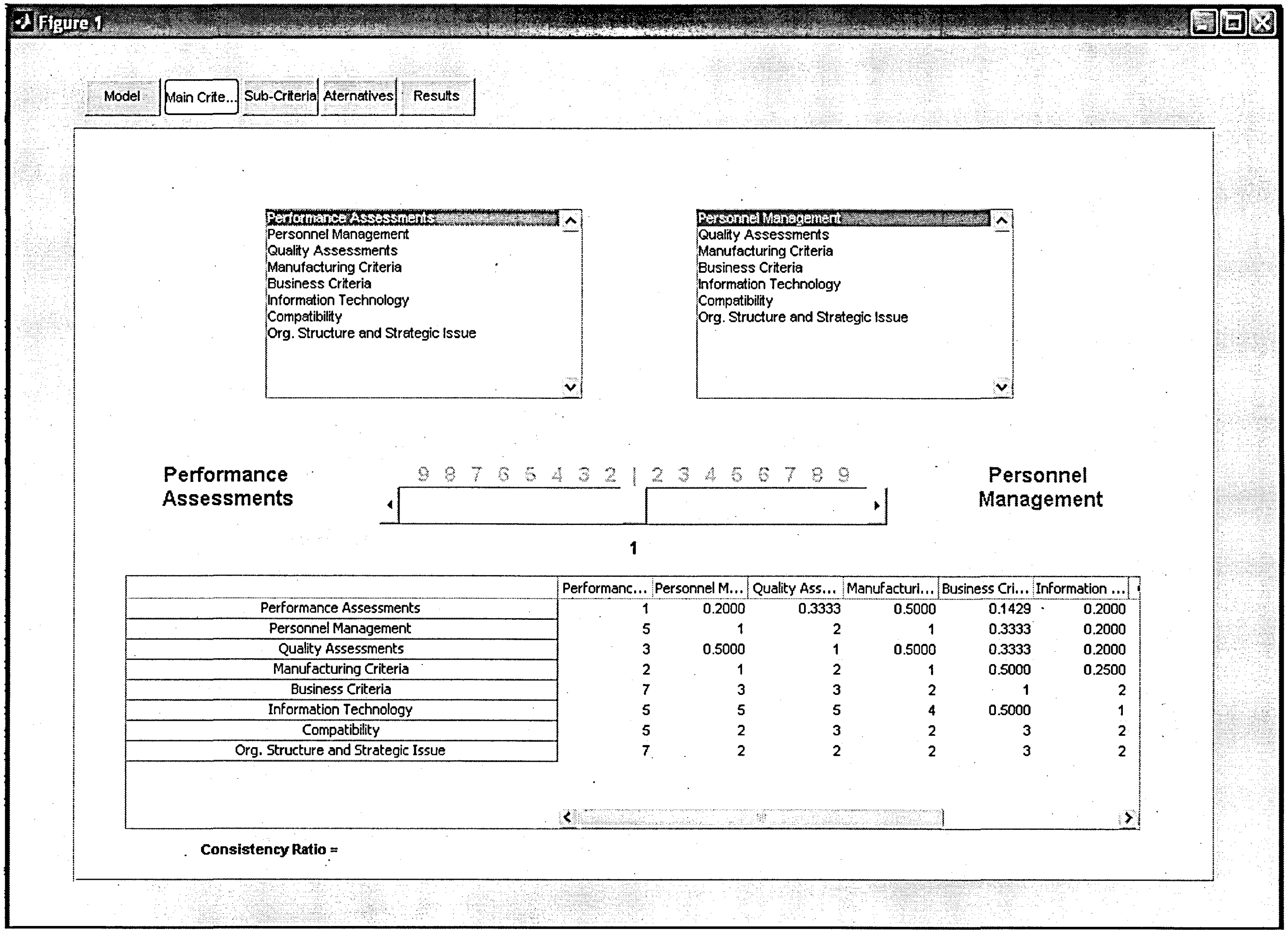


Figure 8.4 Main Criteria

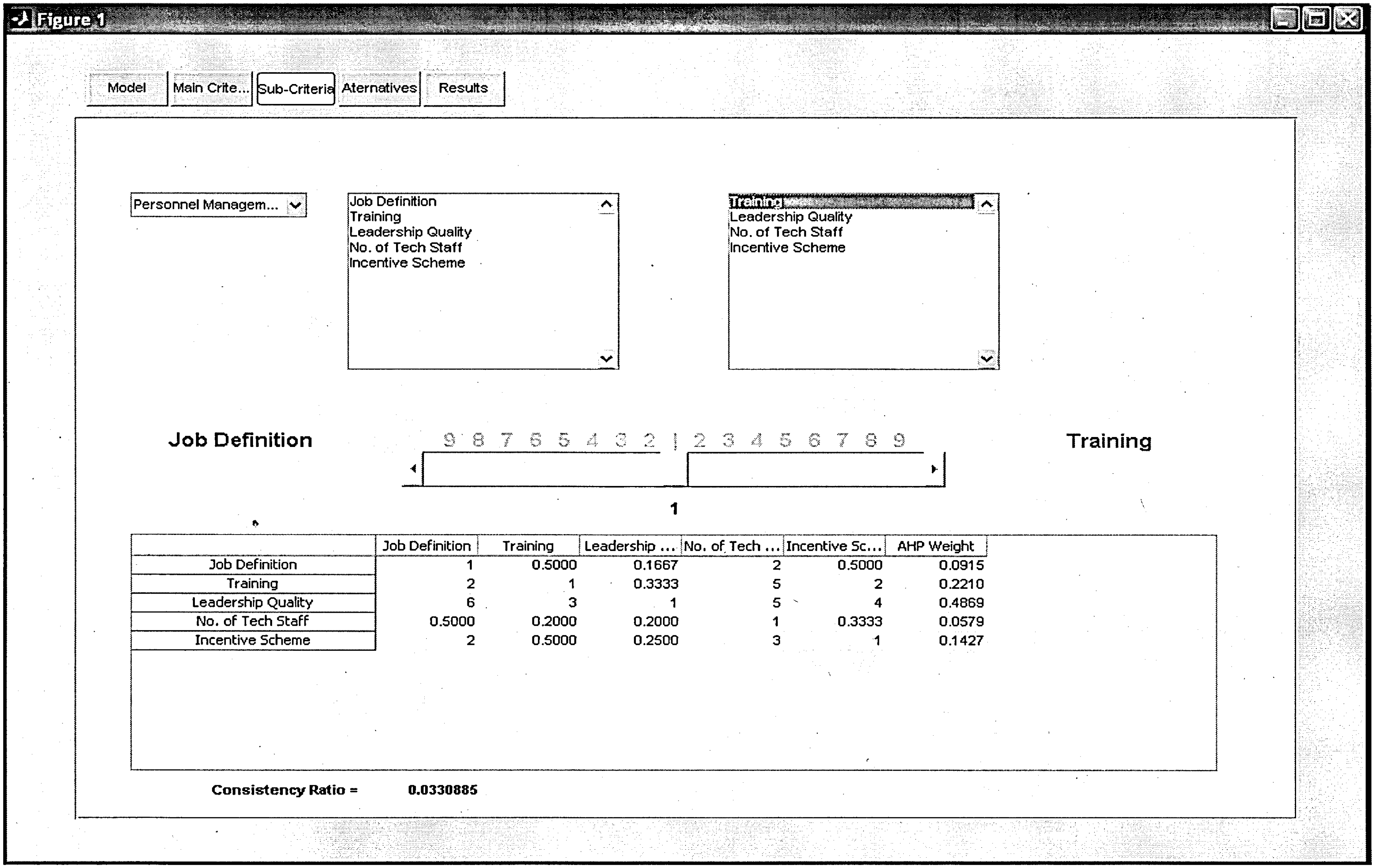
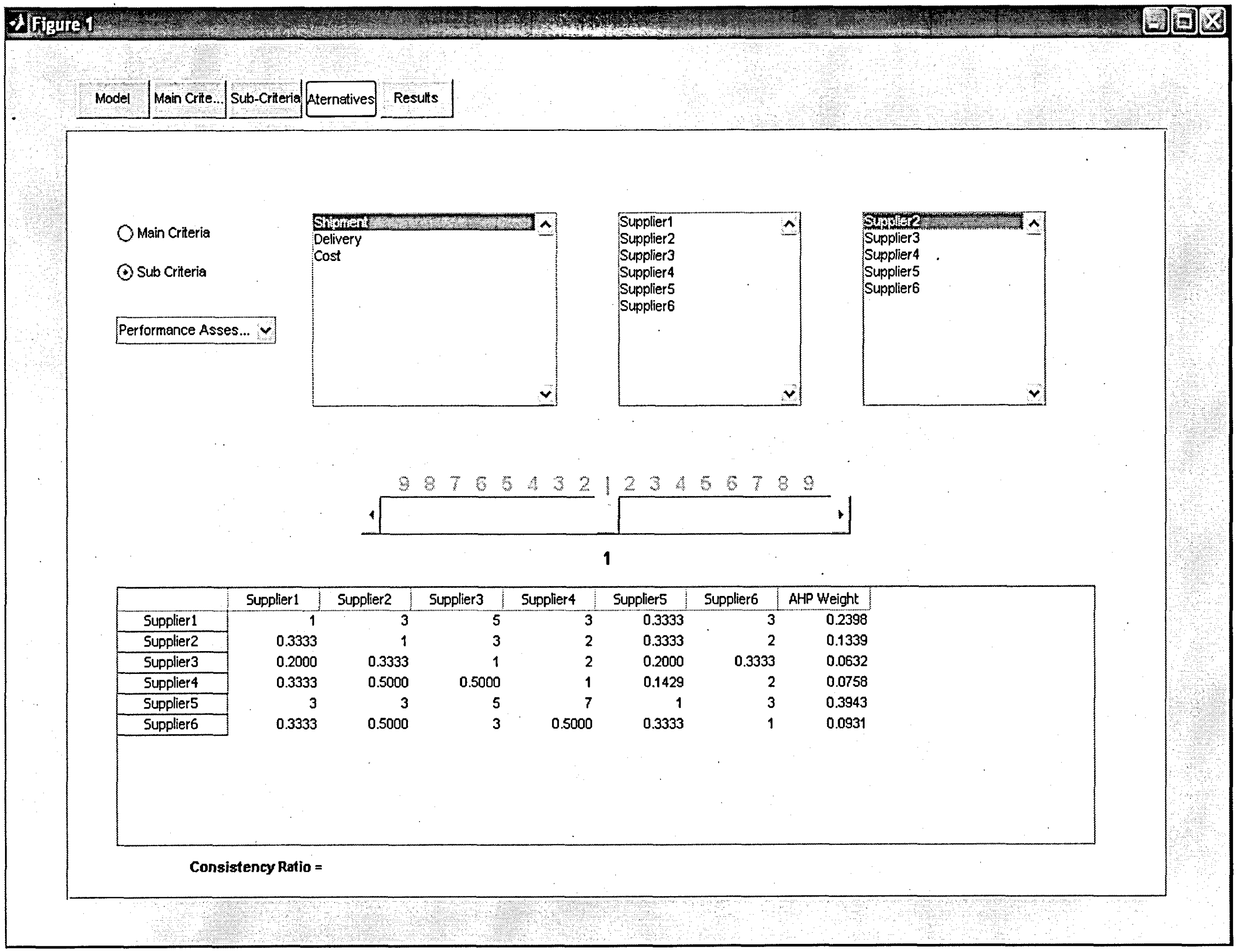
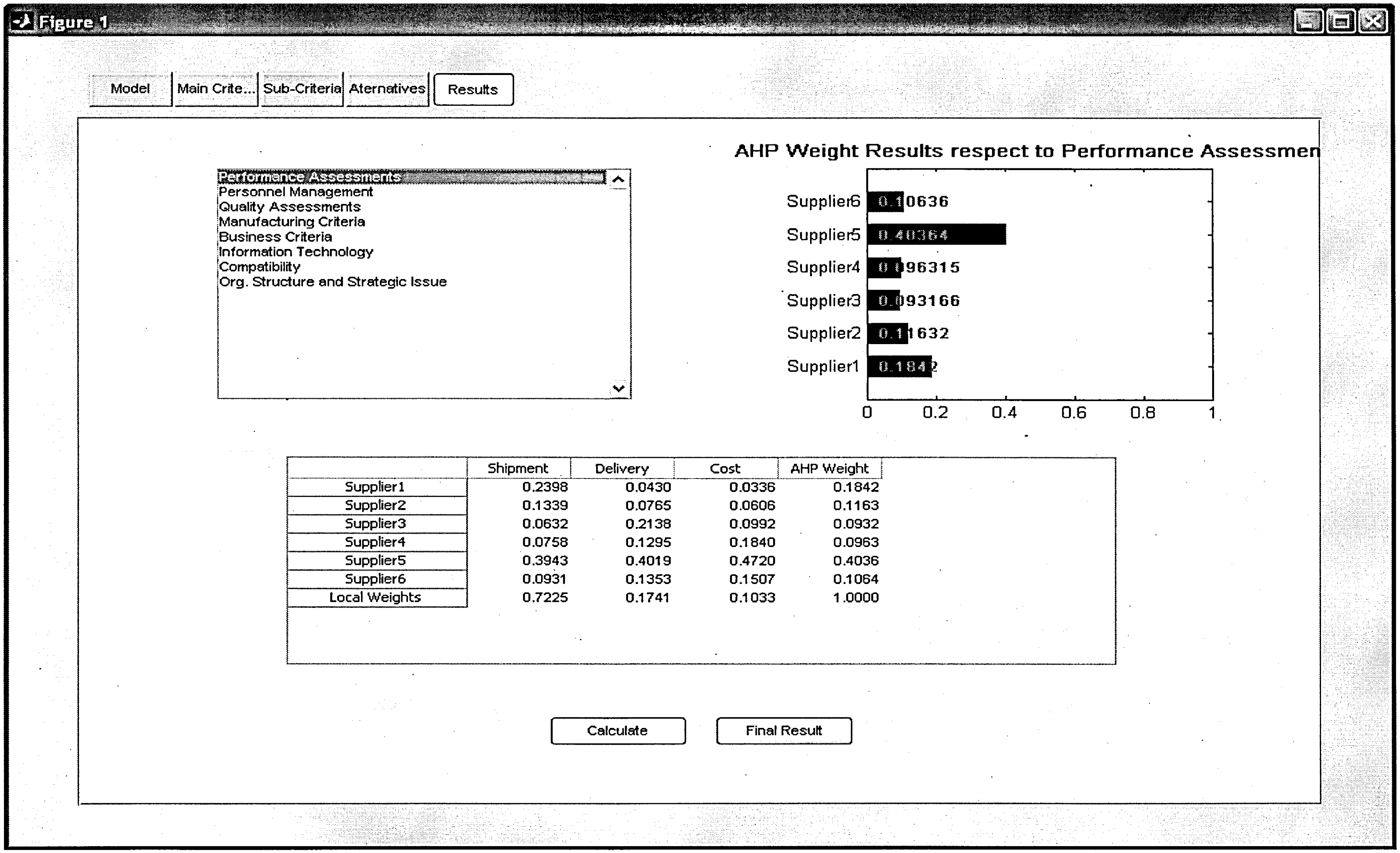


Figure 8.5 Sub-criteria



	Supplier1	Supplier2	Supplier3	Supplier4	Supplier5	Supplier6	AHP Weight
Supplier1	1	3	5	3	0.3333	3	0.2398
Supplier2	0.3333	1	3	2	0.3333	2	0.1339
Supplier3	0.2000	0.3333	1	2	0.2000	0.3333	0.0632
Supplier4	0.3333	0.5000	0.5000	1	0.1429	2	0.0758
Supplier5	3	3	5	7	1	3	0.3943
Supplier6	0.3333	0.5000	3	0.5000	0.3333	1	0.0931

Figure 8.6 Alternatives



	Shipment	Delivery	Cost	AHP Weight
Supplier1	0.2398	0.0430	0.0336	0.1842
Supplier2	0.1339	0.0765	0.0606	0.1163
Supplier3	0.0632	0.2138	0.0992	0.0932
Supplier4	0.0758	0.1295	0.1840	0.0963
Supplier5	0.3943	0.4019	0.4720	0.4036
Supplier6	0.0931	0.1353	0.1507	0.1064
Local Weights	0.7225	0.1741	0.1033	1.0000

Figure 8.7 Local Scores for main criteria (Output)

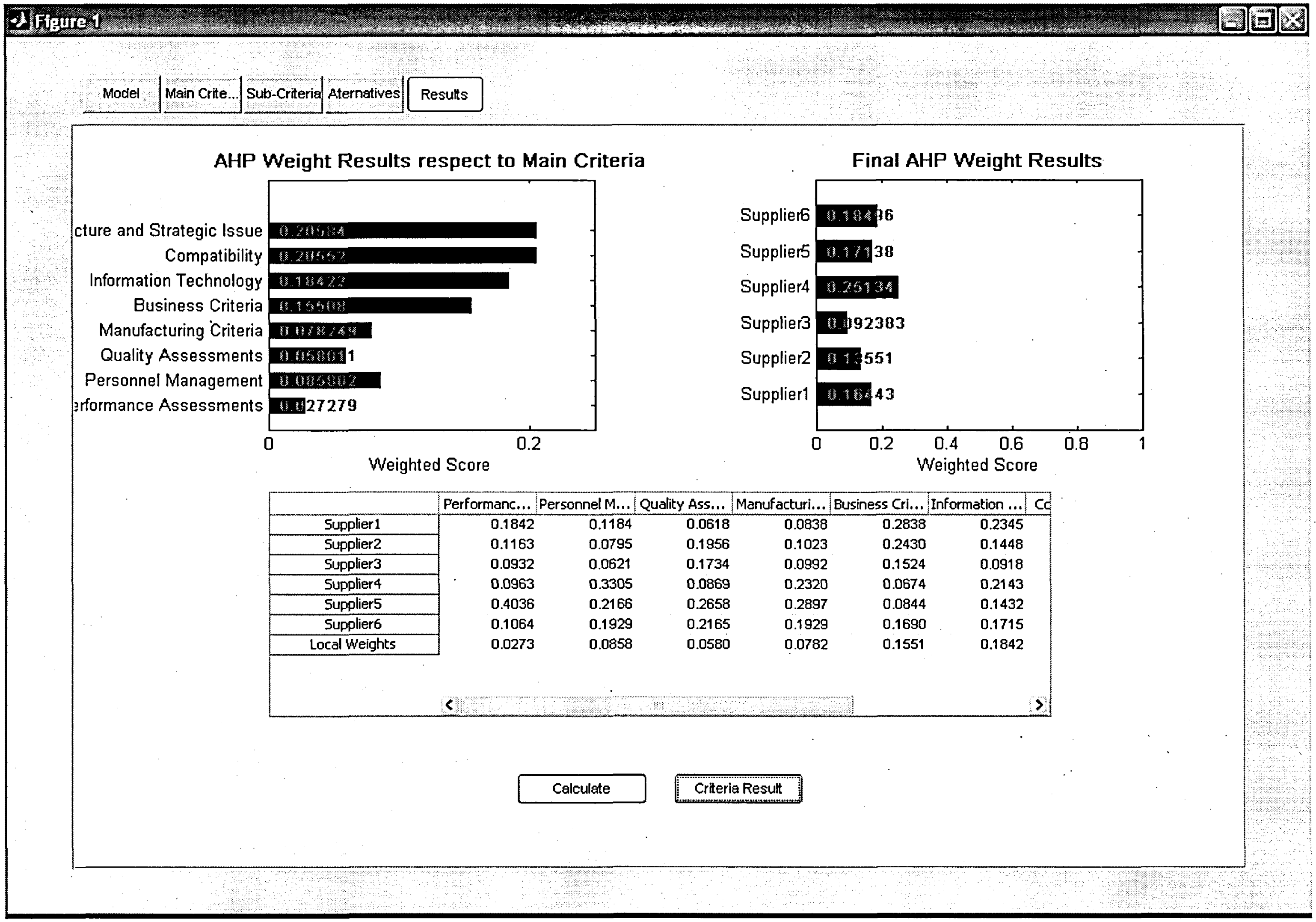


Figure 8.8 Final Score of main criteria and the AHP model Output

8.7 Model results and discussions

The results/ outcome of the various experiments carried out on the model are shown below. The results from individual alternatives have been included under each main criterion. These are shown on (tables 8.3 to 8.10). The comparison matrix for the main criteria is shown on (table 8.11) along with the weighted AHP MATLAB scores on (figure 8.8). The final results of the experimentation are displayed on (table 8.12) along with the final AHP weighted scores (figure 8.10).

a. Performance Assessments

	Shipment	Delivery	Cost	AHP Value
Supplier 1	0.2398	0.043	0.0336	**0.1842**
Supplier 2	0.1339	0.0765	0.0606	**0.1163**
Supplier 3	0.0632	0.2138	0.0992	**0.0932**
Supplier 4	0.0758	0.1295	0.184	**0.0963**
Supplier 5	0.3943	0.4019	0.472	**0.4036**
Supplier 6	0.0931	0.1353	0.1507	**0.1064**
Local Weights	0.7225	0.1741	0.1033	1

Table 8.3 Alternative scores for Performance Assessment

b. Personnel Management

	Job Definition	Training	Leadership	Technical Staff	Incentive Scheme	AHP Value
Supplier 1	0.4126	0.1241	0.0907	0.083	0.0527	**0.1184**
Supplier 2	0.2012	0.0571	0.0523	0.2428	0.0794	**0.0795**
Supplier 3	0.1317	0.0357	0.0357	0.1931	0.1099	**0.0621**
Supplier 4	0.0381	0.4302	0.4088	0.0711	0.144	**0.3305**
Supplier 5	0.0903	0.1681	0.2062	0.294	0.383	**0.2166**
Supplier 6	0.1261	0.1849	0.2062	0.116	0.231	**0.1929**
Local Weights	0.0768	0.2575	0.4724	0.0566	0.1367	1

Table 8.4 Alternative scores for Personnel Management

c. Quality Assessment

	Management Commitment to Quality	Improvement Program	Quality Improvement	Advance Quality Technique	AHP Value
Supplier 1	0.0743	0.0457	0.0509	0.0649	**0.0618**
Supplier 2	0.1607	0.0805	0.2903	0.3204	**0.1956**
Supplier 3	0.1477	0.2188	0.1682	0.1927	**0.1734**
Supplier 4	0.0523	0.1462	0.0717	0.1286	**0.0869**
Supplier 5	0.3526	0.3249	0.1818	0.0492	**0.2658**
Supplier 6	0.2123	0.1839	0.2371	0.2442	**0.2165**
Local Weights	0.426	0.2082	0.226	0.1398	1

Table 8.5 Alternative scores for Quality Assessment

d. Manufacturing Criteria

	Production	Flexibility	Lead-Time	Inventory Handling	Up-to-Date Technique	New Product Development	AHP Value
Supplier 1	0.0527	0.1241	0.083	0.0527	0.083	0.0527	**0.0838**
Supplier 2	0.0794	0.0571	0.2428	0.0794	0.2428	0.0794	**0.1023**
Supplier 3	0.1099	0.0357	0.1931	0.1099	0.1931	0.1099	**0.0992**
Supplier 4	0.144	0.4302	0.0711	0.144	0.0711	0.144	**0.232**
Supplier 5	0.383	0.1681	0.294	0.383	0.294	0.383	**0.2897**
Supplier 6	0.231	0.1849	0.116	0.231	0.116	0.231	**0.1929**
Local Weights	0.0361	0.3557	0.0956	0.2135	0.0932	0.2059	1

Table 8.6 Alternative scores for Manufacturing Criteria

e. Business Criteria

	Reputation	Location	Cost Structure	AHP Value
Supplier 1	0.4126	0.0509	0.0649	**0.2838**
Supplier 2	0.2012	0.2903	0.3204	**0.243**
Supplier 3	0.1317	0.1682	0.1927	**0.1524**
Supplier 4	0.0381	0.0717	0.1286	**0.0674**
Supplier 5	0.0903	0.1818	0.0492	**0.0844**
Supplier 6	0.1261	0.2371	0.2442	**0.169**
Local Weights	0.6325	0.0694	0.2981	1

Table 8.7 Alternative scores for Business Criteria

f. Information technology

	RFID	EDI	Process Improvement	CIM	Communication System	AHP Value
Supplier 1	0.4126	0.0907	0.0545	0.4448	0.1241	**0.2345**
Supplier 2	0.2012	0.0523	0.2916	0.1797	0.0571	**0.1448**
Supplier 3	0.1317	0.0357	0.1554	0.1273	0.0357	**0.0918**
Supplier 4	0.0381	0.4088	0.0729	0.0368	0.4302	**0.2143**
Supplier 5	0.0903	0.2062	0.1878	0.0879	0.1681	**0.1432**
Supplier 6	0.1261	0.2062	0.2379	0.1235	0.1849	**0.1715**
Local Weights	0.0373	0.0848	0.1666	0.3556	0.3556	1

Table 8.8 Alternative scores for Performance Assessments criteria

g. Compatibility

	Level of Trust & Understanding	Cultural Similarity	AHP Value
Supplier 1	0.1241	0.0907	**0.1074**
Supplier 2	0.0571	0.0523	**0.0547**
Supplier 3	0.0357	0.0357	**0.0357**
Supplier 4	0.4302	0.4088	**0.4195**
Supplier 5	0.1681	0.2062	**0.1871**
Supplier 6	0.1849	0.2062	**0.1956**
Local Weights	0.5	0.5	1

Table 8.9 Alternative scores for Compatibility criteria

h. Organisational Structure and Strategies

	Organisational Structure	Management Commitment	Learning Culture	AHP Value
Supplier 1	0.4126	0.0649	0.1241	**0.1448**
Supplier 2	0.2012	0.3204	0.0571	**0.1485**
Supplier 3	0.1317	0.1927	0.0357	**0.0914**
Supplier 4	0.0381	0.1286	0.4302	**0.2964**
Supplier 5	0.0903	0.0492	0.1681	**0.1252**
Supplier 6	0.1261	0.2442	0.1849	**0.1937**
Local Weights	0.1285	0.2766	0.5949	1

Table 8.10 Alternative scores for Organisational Structure and Strategies

Main Criteria

	Output 1	Output 2	Output 3	Output 4	Output 5	Output 6	Output 7	Output 8	AHP Weight
Performance Assessments	1	1/5	1/3	1/2	1/7	1/5	1/5	1/7	**0.027**
Personnel Management	5	1	2	1	1/3	1/5	1/2	1/2	**0.086**
Quality Assessments	3	1/2	1	1/2	1/3	1/5	1/3	1/2	**0.058**
Manufacturing Criteria	2	1	2	1	1/2	1/4	1/2	1/2	**0.078**
Business Criteria	7	3	3	2	1	2	1/3	1/3	**0.155**
Information Technology	5	5	5	4	1/2	1	1/2	1/2	**0.184**
Compatibility	5	2	3	2	3	2	1	1	**0.206**
Org. Structure and Strategic Issue	7	2	2	2	3	2	1	1	**0.206**

Table 8.11 Comparison matrix for main criteria

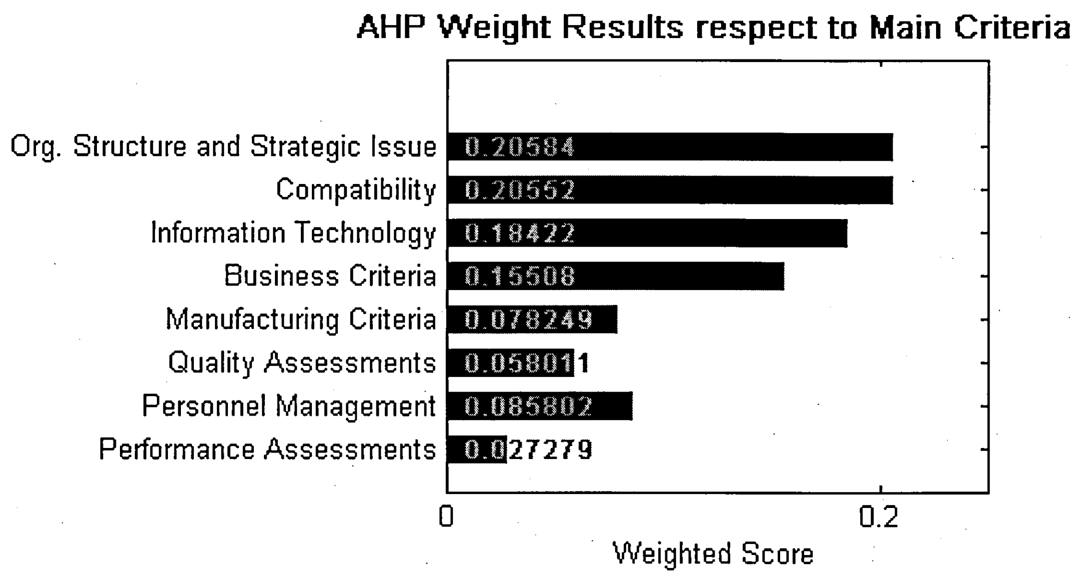


Figure 8.9 AHP results for comparison matrix

Final Result

	Performance Assessments	Personnel Management	Quality Assessments	Manufacturing Criteria	Business Criteria	Information Technology	Compatibility	Org. Structure and Strategic Issue	AHP Weight
Supplier 1	0.1842	0.1184	0.0618	0.0838	0.2838	0.2345	0.1074	0.1448	**0.1644**
Supplier 2	0.1163	0.0795	0.1956	0.1023	0.243	0.1448	0.0547	0.1485	**0.1355**
Supplier 3	0.0932	0.0621	0.1734	0.0992	0.1524	0.0918	0.0357	0.0914	**0.0924**
Supplier 4	0.0963	0.3305	0.0869	0.232	0.0674	0.2143	0.4195	0.2964	**0.2513**
Supplier 5	0.4036	0.2166	0.2658	0.2897	0.0844	0.1432	0.1871	0.1252	**0.1714**
Supplier 6	0.1064	0.1929	0.2165	0.1929	0.169	0.1715	0.1956	0.1937	**0.185**
Local Weights	0.0273	0.0858	0.058	0.0782	0.1551	0.1842	0.2055	0.2058	

Table 8.12 Final Result

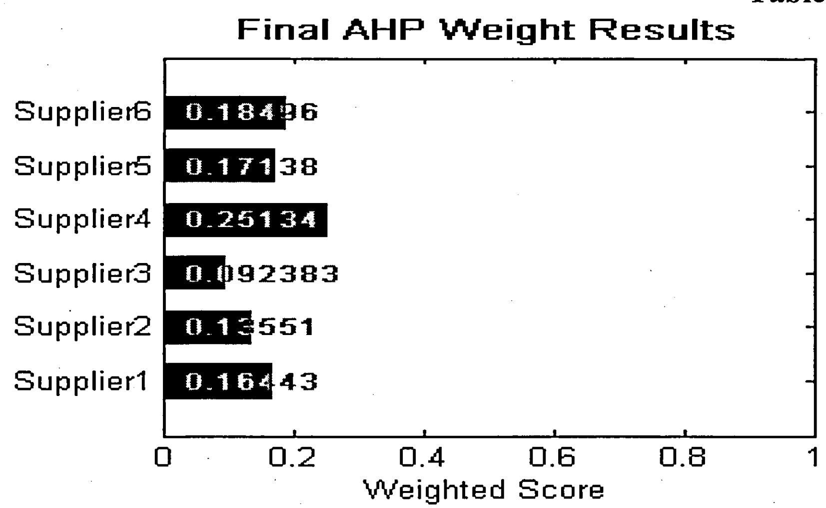


Figure 8.10 Final outcome of AHP model

8.7.1 Discussions

The hypothetical data was fed into the model accordingly and the overall results show that supplier 4 came out as the top supplier, doing well in both tangible and intangible criteria. Supplier 4 ranked well in personnel management, manufacturing criteria, information technology and compatibility which attributes are at the heart of alliances and collaborations as found in the FMP. This is based on the judgement that these criteria will help the fractal company survive a long term relationship. The fractal company advocates a great learning, 'open book' culture and more sophisticated communication link between fractals in order to maintain the transparency of information and to facilitate continuous improvement program and Research and Development.

Supplier 6 follows, but not closely in the ranking, doing relatively well in quality assessment, organisational structure and strategy and personnel management. Supplier 6 possesses moderate aspects of the tangible and intangible criteria. Ranking third amongst the six suppliers is supplier 5, but not surprisingly since it scores well in performance assessment, quality assessment, manufacturing criteria which are solidly tangible criteria. Supplier 3 occupies bottom of the list amongst the six suppliers.

The AHP methodology implemented using MATLAB as seen above has proved very effective in solving the FMP supplier selection problem by formulating a framework for evaluating and choosing between seemingly conflicting criteria. It could accommodate subjective and uncertain information in terms of both tangible and intangible criteria in a logical manner. However, there are a few negligible drawbacks due to the limitation of AHP. The AHP process is driven by the decision makers' preferences and there is no way to verify the outcome. The final results are based on the perception of the decision makers on the criteria and alternatives as in the experiment, intangible result is seen to be more important. The final result reflects this line of judgement.

8.8 Conclusion

Selection and maintenance of high quality and reliable Suppliers is a key component of the successful implementation of FMP. One objective of the selection process is determination of optimal supplier criteria particularly suited to the fractal manufacturing company philosophy. This chapter has reviewed conventional criteria used mainly in the buyer-supplier/ procurement selection process and short listed some important criteria which are relevant to the FMP. These criteria are classified in two categories known as tangible and intangible depending on how perceptible or realistic they are. A mathematical argument is also put forward to justify the process of the supplier selection.

To further evaluate the importance of each criterion to FMP, this study utilizes the AHP methodology implemented using MATLAB programming language to generate a framework that robustly identifies different criteria most of which are conflicting, and suppliers to obtain an optimal choice. This approach is flexible enough to allow decision makers to make their preferences in a qualitative manner while the framework transforms the decision into quantitative results and helps in selecting the right set of suppliers without undermining the inherent strengths of the FMP.

Chapter Nine

9.0 Conclusions, contributions to knowledge, limitations and further work

This chapter draws concluding remarks, summaries and generalization of the research. It addresses various achievements of the project. The key, original contributions of the research to knowledge in the area/ field of manufacturing are placed in perspective, articulated and set against the research questions as well as the main aims and key objectives of the research and how far these targets have been satisfied/ met. The chapter ends with suggestions and recommendations and further works.

9.1 Summery of research

The quest for variety and individualistic desires on the part of customers, continuing focus on agile manufacturing and reduction in lead times and batch sizes on the part of manufacturers and general need for revolutionary developments will make the need for greater operational flexibility and ability of systems to transform their internal structures over the next decade more imperative. To meet the needs of a volatile and unpredictable market, current organisational structures will have to be replaced by distributed, autonomous, more innovative organisational structures. This method of operation will be more in line with managing multi-functional projects, stimulating innovative ideas and new knowledge. To this end, many new concepts and proposals are being made in the academia. These include; Agile manufacturing (Gunasekaran 1998, Sharifi and Zhang 2001), Biological or bionic manufacturing system (BMS) (Okino 1992, Okino 1993, Ueda 1992, Ueda 1993, Ueda 1997b, Ueda 2001a), Holonic manufacturing system (HMS) (Seidel *et al.* 1994, Valckenaers *et al.* 1994, Van Brussel et al. 1998, McFarlane and Bussman 2000), Fractal manufacturing system (FrMS) (Tirpak 1992, Warnecke 1993, Venkatadri et al. 1997, Ryu *at al.* 2000, 2001, Ryu and Jung 2002) and responsive manufacturing (Gindy *et al.* 1996, Saad and Gindy 1998). These paradigms have very promising features but the literatures on them are very limited because they have been narrowly based on the basic shop floor operations and management. The wider, more important issues of supply chain management implementation have been crucially left out.

FrMS is the subject of this study. It was shown in the course of the research to conceptually prove and promise a viable option in tackling 21st century dynamic manufacturing concerns providing flexibility, adaptability, agility, and dynamic re-configurability (Deen, S.M., 2003), which core requisites are needed to face new industrial challenges. The research extensively investigated the FrMS and used the fractal architecture to develop lean and agile ('leagile') capability (Saad, S., and Aririguzo, J., 2007a) to bridge supply chain gap left by the EMS, bringing OEM and key suppliers closer in a novel relationship (FMP) (Saad, S., and Aririguzo, J., 2009) and finally formulating methods of selecting quality suppliers to go into the partnership.

9.1.1 The fractal internal design

A new approach, the Genetic Algorithm approach was used to design the fractal shop floor layout in chapter five. This chapter contributed significantly to solving research question one. Originally, the fractal layout design was spearheaded by Venkatadri *et al.* (1997) who based their method on the fractal cell design, with no clear definition for the multiple design parameters involved in the fractal cell configuration, hampering the methods applicability. The GA approach used in this study paid particular attention to the determination of capacity level, cell composition and flow distances. It turns out that the proposed GA approach worked out better than (Venkatadri *et al.* 1997).

9.1.2 The fractal supply network

The fractal architecture was applied in the integration of lean manufacturing and agile capabilities in a total supply network in chapter six. This was achieved through continuous monitoring, re-positioning and improvement of the decoupling point and a savvy management of effective supply chain and networks (Saad, S., and Aririguzo, J., 2007a), to systematically streamline, coordinate and manage activities, processes and information. The downstream effects/ results were reduced inventory, less emphasis on fire fighting, reduced cost and cycle times. The gains made in this chapter went a long way in answering research question two as well as question three.

9.1.3 Integrating the OEM and suppliers

Simulation model development of the integration of OEM and key suppliers (FMP) was made in chapter seven. The key focus was on harmonizing as well as synchronizing the operations of this network of suppliers who have become <u>assemblers</u> of their components while co-existing side by side with one another on the assembly line, sharing the OEMs' facility and a common database of information (Saad, S., and Aririguzo, J., 2008 & 2009). The synergic effect of this collaboration was shown to promote a heightened sense of responsibility amongst parties. The achievements made in this chapter contributed immensely to solving research questions one, two and three.

9.1.4 Supplier selection in FMP

A framework was put forward for selection and maintenance of high quality and reliable suppliers to go into the FMP in chapter eight. This was achieved through formulation of comprehensive supplier selection criteria using analytical hierarchy process (AHP) approach. This methodology was implemented using MATLAB to generate a robust catalogue of criteria which informed and allowed decision makers to make their choices in a qualitative and informed manner. The work done in this chapter helped in answering research questions two and three.

9.2 General view of the research

The full picture of the research was the development of the conceptual FrMS so as to bring this into a logical and comprehensible order, gearing towards full industrial implementation. The fractal architecture was used in the establishment of 'leagile' enterprises - an integration of lean and agile capabilities in a total supply network. Relying on effective supply chains or networks and their savvy management is the key to surviving and thriving in the 21st century capricious global market. It was demonstrated that the fractal architecture proposed in this research could harness and drive the shift and evolution from rigidly vertically integrated company, to a decentralized network of integrated, maximized, leaner core competencies needed to tackle and weather the storm of the manufacturing system as well as cushioning the blow of erratic customer behaviour. The high level of responsiveness (formed as a result) and information enrichment in the FMP essentially equips enterprises with necessary flexibility and robustness to monitor, plan, control and grab opportunities in newer markets as well as stand challenges brought by advancement in technology.

9.3 Generalization of the research outcome

In the course of this research, the concept of fractal architecture has been studied and typified by the automotive industry, by applying the concept wholly in new alliances between automotive OEMs and their key suppliers in the car making industry. This sector readily embodies essential characteristics of the fractal system. It is established that the proposed fractal system is most suitable for engineering assembly type of work in which seamless operation is desired and where agile feedback is necessary (Saad and Aririguzo, 2007). However, this notion/ concept can be extended to other areas and related disciplines - service sector and extraction industry (mining, construction, and agriculture) etc. Separate or individual components of the fractal architecture can be applied to improve existing systems. For instance, the leagile network aspect of the architecture lends itself to a broad range of industries where leanness and agility is required due to the need to react swiftly and effectively to erratic customer attitudes and fast evolving of technology.

9.4 Limitations and weaknesses of research

Most of the new proposals and developments made in this research are based on hypothetical experimentations. The FrMS while still in the conceptual and developmental stages has not been widely industrially implemented, and therefore real data were far fetched. Most of the data used for the experimentation during this study were made up. However, these data were comprehensively validated and statistical confidence interval/ levels of 95% or above were fitted to the results to ensure their reliability. Having said this, other assumptions were made during the experiments and these were discussed in the relevant chapters of the thesis. In terms of applicable software, the modelling of FMP was restricted to the confines of Arena simulation software, which is very limiting because it could not represent or effectively and explicitly model the fractal specific characteristics. The development of interfaces for different softwares would definitely be an advantage on this front.

9.5 Research original contribution

In the course of the research, an in-depth investigation of the FrMS was made and the distinct characteristic features of the fractal organization were made instantly identifiable. The fractal architecture was used to develop 'leagile' networked capabilities in a total supply network, bringing OEMs and their key suppliers together in a new partnership (FMP), where these suppliers became assemblers of their components. The supply chain becomes synchronous and functional, enhancing the flow of resources and information. The following major contributions were made by the research to manufacturing system and knowledge;

- Instantly identifiable characteristic features of the fractal company were identified and differentiated from that of other Emerging Manufacturing Systems.
- Distinctions were made between traditional manufacturing method, the EMS in general and FrMS in particular.
- A new approach, the GA approach was used in the design of the fractal shop floor layout paying particular attention to the determination of capacity level and cell composition.

- Integration of OEM and key suppliers was made in a revolutionary partnership (FMP) to achieve reduction in management, high level of responsiveness, and improved design for manufacture as suppliers become assemblers.
- Built and developed a virtual scenario for the proposed FMP to identify all bottlenecks and maximizing the potentials of the partnership.
- Identifying the best fit and balance for the OEM/ supplier partnership to ensure a harmonious collaboration, and robustness of the alliance in the face of uncertainties (unforeseen delays and machine breakdowns).
- Calculating the best mix of resource capacities to maximise throughput in the integration of lean production/ agile network capabilities.
- Developed savvy integration of the lean and agile paradigms (leagility') in a total supply network for smooth flow of resources and information, reduced inventory and consequently less emphasis on fire fighting.
- Finding the optimal balance for the system in a volatile environment/ market while meeting the conceptual benefits of the FrMS, including an improved product quality.
- Designing a framework for the supplier selection criteria prior to the FMP using AHP approach.
- The afore mentioned developments constitute comprehensive, core components of a "Fractal Architecture for leagile networked enterprises' that can help practitioners in making robust and informed decision in designing, planning, modelling, and controlling their manufacturing environments.

9.6 Further works

There is no room for complacency in the pursuit of the 21st century 'ideal' manufacturing system. This remains to be comfortably realised. It has been shown in this research that the EMS are in the development stages and still hazy, without clear plan for industrial implementation going forward. Therefore, researchers and industrialists have to continue building on the gains and the successes made so far. Further work is needed to put them into standard practice and implementation. A lot needs to be done especially in the following areas;

1. In the area of software development, model development and exchange is restricted

within the confines of Arena simulation software. Arena is limiting in its capability to model and represent the fractal specific characteristics.

2. Model exchange should be extended to other simulation softwares to represent both procedural and object-oriented perspectives, with potential appropriate development of interfaces.
3. Re-usable set of model elements or templates should be developed and dedicated to the characteristic features of fractals with neutral flowcharts attributes that can describe the model explicitly and independently.
4. An integrated documentation process/ model development process will track and improve the documentation of the modelling/ simulation project. This will easily manage, control and monitor the progress of the project.
5. To create and enhance an information enriched environment for the FMP, it is imperative that open but unified methods in communication and protocols for the exchange of manufacturing data, at cell level with robust interfaces are integrated during planning or design stages.
6. More work needs to be done in the area of cultural integration and cohesion of these network of suppliers residing side-by-side in this open book relationship, because win, lose or draw, a business can only be as good as its people.

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Appendix

Appendix A: MATLAB code for supplier selection criteria in FMP

```
% - criteria array
%     main criteria
%     subcriteria_cell
% - alternative array
%     alternatives
% -criteria data/properties
%     -data
%     -subcriteriacell_size

function varargout
close all;
clc;
f = figure('Visible','on',...
    'Position', [140 37 1000 700],...
    'Menubar', 'none');
%     movegui(f, 'center');
select_color = [0.75, 0.75, 0.75];
default_color = [0.9255,    0.9137,    0.8471];

%     Criteria defination
main_criteria = {'Performance Assessments';'Personnel
Management';'Quality Assessments';'Manufacturing Criteria';...
    'Business Criteria';'Information Technology';'Compatibility';'Org.
Structure and Strategic Issue'};
subcriteria(:,1) = {'Shipment'; 'Delivery'; 'Cost';'';'';''};
subcriteria(:,3) = {'Management commitment to Quality'; 'Improvement
Program';'Quality Improvement'; 'Advance Quality Technique';'';''};
subcriteria(:,4) = {'Production Capacity';'Flexibility';'Lead-time';
'Inventory Handling';...
    'Up-to Date Technique';'New Product Developement'};
subcriteria(:,2) = {'Job Definition';'Training';'Leadership Quality'; 'No.
of Tech Staff';'Incentive Scheme';''};
subcriteria(:,5) = {'Reputation'; 'Geographical Location';'Cost
Structure';'';'';''};
subcriteria(:,6) = {'RFID'; 'EDI';'Internet';'CIM';'Communication
Systems';''};
subcriteria(:,7) = {'Level of Trust and Understanding';
'Negotiability';'';'';'';''};
subcriteria(:,8) = {'Organisational Structure'; 'Management
Commitment';'Learning Culture';'';'';''};


alternatives = {'Supplier1'; 'Supplier2';
'Supplier3';'Supplier4';'Supplier5';'Supplier6'};
%pre_data = importdata('ahp.dat');

%     Criteria defination end

%     Create main criteria numeriacal array
x=1;
while (x<=max(length(main_criteria)))
    y=1;
    while (y<=max(length(main_criteria)))
        if (x==y)
            data(x,y,1,1)={1};
```

```
        else
            data(x,y,1,1) = {0};
        end
        ahp_data(x,1) = {[]};
        y=y+1;
    end
    x=x+1;
end
%final_data = [data(:,:,1,1)  ahp_data];
%disp(final_data);
main_size = length(main_criteria);
%     Create main criteria numerical array end
%disp(cell2mat(data(:,:,1,1)));
%abb=cell2mat(data(:,:,1,1));
%disp(sum(sum(abb(:,:,1,1))));
%     subcriteria properties
subcriteria_size = size(subcriteria);
x = 1;
while x <= subcriteria_size(1,2)
    y = 1;
    while (y <= subcriteria_size(1,1))
        a = subcriteria(y,x);
        if (isempty(cell2mat(a))==1)
            break
        else
            subcriteria_cell(y,x) = subcriteria(y,x);
            subcriteriacell_size(x)=y;
            y=y+1;
        end
    end

    x=x+1;
end
%     subcriteria properties end

%     Create sub criteria numerical array

z=1;
while (z<=max(main_size))
    x=1;
    while (x<=subcriteriacell_size(z))
        y=1;

        while (y<=subcriteriacell_size(z))

            if (x==y)
                data(x,y,z+1,1)={1};
            else
                data(x,y,z+1,1) = {0};
            end
            y=y+1;

        end
        ahp_data(x,1,z+1,1) = {[]};
        x=x+1;
    end
    z=z+1;
end

%     Create sub criteria numerical array end
```

```
%xlswrite('ahp.xlsx', ahp_data(:,:,:,1));
%     Create Alternatives numerical array
alter_size = max(length(alternatives));
total_criteria_size(2:length(subcriteriacell_size)+1)...
    = subcriteriacell_size(1:length(subcriteriacell_size));
total_criteria_size(1)=max(main_size);
%disp(total_criteria_size);
elements_size = max(length(total_criteria_size));
%disp(total_criteria_size);
w = 1;
while (w<=elements_size)
    z=1;
    while (z<=total_criteria_size(w))
        x=1;
        while (x<=alter_size)
            y=1;
            while (y<=alter_size)
                if (x==y)
                    data(x,y,z,w+1)={1};
                else
                    data(x,y,z,w+1) = {0};
                end
                y=y+1;
            end
            ahp_data(x,1,z,w+1) = {[]};
            x=x+1;
        end
        z=z+1;
    end
    w=w+1;
end
        x=1;
        y=1;
        while x<=subcriteria_size(1,2)
            p=1;
            y=1;
            while y<=subcriteria_size(1,1)
                a = subcriteria(y,x);
                if (isempty(cell2mat(a))==1)
                    break
                else
                    sub_size(x)=p;
                    p=p+1;
                    y=y+1;
                end
            end
            x = x+1;
        end
%disp(data(:,:,:,:));
%     Create Alternatives numerical array end

%     Initialise basic Graphic User Interface
%     Create Tabs and Panels
toggletab1 = uicontrol(...
    'Position',[60 640 60 30],...
    'backgroundcolor', default_color,...
    'Callback', @toggletab1_Callback,...
    'ToolTipString' , 'Model View',...
    'String', 'Model'...
    );
```

```
toggletab2 = uicontrol(...
    'Position',[122 640 60 30],...
    'backgroundcolor', select_color,...
    'Callback', @toggletab2_Callback,...
    'ToolTipString' , 'Pairwise Numerical Comparison',...
    'String', 'Main Criteria'...
    );
toggletab3 = uicontrol(...
    'Position',[184 640 60 30],...
    'backgroundcolor', select_color,...
    'Callback', @toggletab3_Callback,...
    'ToolTipString' , 'Sub-Criteria',...
    'String', 'Sub-Criteria'...
    );
toggletab4 = uicontrol(...
    'Position',[246 640 60 30],...
    'backgroundcolor', select_color,...
    'Callback', @toggletab4_Callback,...
    'ToolTipString' , 'Aternatives',...
    'String', 'Aternatives'...
    );
toggletab5 = uicontrol(...
    'Position',[308 640 60 30],...
    'backgroundcolor', select_color,...
    'Callback', @toggletab5_Callback,...
    'ToolTipString' , 'AHP Results',...
    'String', 'Results'...
    );
toggletab6 = uicontrol(...
    'Position',[370 640 60 30],...
    'backgroundcolor', select_color,...
    'Callback', @toggletab6_Callback,...
    'ToolTipString' , '',...
    'String', '', 'Visible', 'off'...
    );

panel1h     = uipanel(...
    'Parent',f,'Title','',...
    'Visible', 'on','Position',[.05 .05 .5 .85]...
    );
panel2h     = uipanel(...
    'Parent',f,'Title','',...
    'Position',[.05 .05 .9 .85], 'Visible', 'off'...
    );
panel3h     = uipanel(...
    'Parent',f,'Title','',...
    'Visible', 'off','Position',[.05 .05 .9 .85]...
    );
panel4h     = uipanel(...
    'Parent',f,'Title','',...
    'Visible', 'off','Position',[.05 .05 .9 .85]...
    );
panel5h     = uipanel(...
    'Parent',f,'Title','',...
    'Visible', 'off','Position',[.05 .05 .9 .85]...
    );
panel6h     = uipanel(...
    'Parent',f,'Title','',...
    'Visible', 'off','Position',[.05 .05 .9 .85]...
    );
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%     Main Tab
criteria    = uicontrol(....
    'Parent', panel1h,'Style','listbox',...
    'String',main_criteria,...
    'Callback', @criteria_Callback,...
    'Value',1,'Position',[40 220 150 150]...
    );
subcriteriah  = uicontrol(...
    'Parent', panel1h,'Style','listbox',...
    'Callback', @listbox2_Callback,...
    'String',subcriteria_cell(:,1),...
    'Value',1,'Position',[220 220 200 150]...
    );
altern  = uicontrol(...
    'Parent', panel1h,'Style','listbox',...
    'Callback', @listbox2_Callback,...
    'String',alternatives,...
    'Value',1,'Position',[40 30 150 150]...
    );
text1 = uicontrol(...
    'Parent', panel1h,...
    'Position',[40 422 70 15],...
    'Style', 'text','FontSize', 10,...
    'String' , 'Objectives:');
text2 = uicontrol(...
    'Parent', panel1h,...
    'Position',[110 420 240 20],...
    'Style', 'edit',...
    'Callback', @text2_Callback...
    );
text3 = uicontrol(...
    'Parent', panel1h,...
    'Position',[40 370 80 15],...
    'Style', 'text','FontSize', 9,...
    'Fontweight', 'bold',...
    'String' , 'Main Criteria');
text4 = uicontrol(...
    'Parent', panel1h,...
    'Position',[220 370 70 15],...
    'Style', 'text','FontSize', 9,...
    'Fontweight', 'bold',...
    'String' , 'Sub-Criteria');
text5 = uicontrol(...
    'Parent', panel1h,...
    'Position',[40 180 70 15],...
    'Style', 'text','FontSize', 9,...
    'Fontweight', 'bold',...
    'String' , 'Alternatives');
%     Tab 2

main_col = main_criteria;
main_col(length(main_criteria)+1) = {'AHP Weights'};
tableh    = uitable(...
    'Data',[data(:,:,1,1)
ahp_data(:,:,1,1)] ,'ColumnName',main_col ,'RowName' , main_criteria,...
    'Parent',panel2h,'Position',[40 40 800 200],...
    'Columnwidth', 'auto',...
    'Columnformat', [char char char char char char char char]...
    );
%   'CellEditCallback' , @tableedit_Callback,...
```

```
% 'CellSelectionCallback' , @table_Callback,...
sliderh  =  uicontrol(panel2h,'Style','slider',...
    'Max',8,'Min',-8,'Value',0,...
    'SliderStep',[0.0625 0.0625],...
    'enable' , 'off',...
    'Callback' , @slider_Callback,...
    'Position',[240 280 400 30]);
text6 = uicontrol(...
    'Parent', panel2h,...
    'Position',[40 270 160 60],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'b',...
    'String' , '');
text_CI = uicontrol(...
    'Parent', panel2h,...
    'Position',[70 10 170 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'String' , 'Consistency Ratio = ');
text_CI2 = uicontrol(...
    'Parent', panel2h,...
    'Position',[220 10 100 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'b',...
    'String' , '');
text_CI_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[70 10 170 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'String' , 'Consistency Ratio = ');
text_CI2_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[220 10 100 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'b',...
    'String' , '');
text_CI_4 = uicontrol(...
    'Parent', panel4h,...
    'Position',[70 10 170 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'String' , 'Consistency Ratio = ');
```

```
text_CI2_4 = uicontrol(...
    'Parent', panel4h,...
    'Position',[220 10 100 20],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 8,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'b',...
    'String' , '');
text7 = uicontrol(...
    'Parent', panel2h,...
    'Position',[680 270 160 60],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'r',...
    'String' , '');
text8 = uicontrol(...
    'Parent', panel2h,...
    'Position',[245 310 390 20],...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', [0.7 0.7 0.7],...
    'String' , '9   8   7   6   5   4   3   2   |   2   3   4   5   6   7
8   9');
text9 = uicontrol(...
    'Parent', panel2h,...
    'Position',[430 250 20 20],...
    'Style', 'text','FontSize', 10,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'backgroundColor', 'w',...
    'String' , '1');
criteria1   = uicontrol(....
    'Parent', panel2h,'Style','listbox',...
    'String',main_criteria,...
    'Callback', @criteria1_Callback,...
    'backgroundcolor', 'w',...
    'Value',1,'Position',[150 380 250 150]...
    );
criteria2   = uicontrol(....
    'Parent', panel2h,'Style','listbox',...
    'Callback', @criteria2_Callback,...
    'backgroundcolor', 'w',...
    'Value',1,'Position',[490 380 250 150]...
    );

table3h   = uitable(...
    'Parent',panel3h,'Position',[40 40 800 200],...
    'Columnwidth', 'auto',...
    'Columnformat', [char char char char char char char char]...
    );

slider3h  =  uicontrol(panel3h,'Style','slider',...
    'Max',8,'Min',-8,'Value',0,...
    'SliderStep',[0.0625 0.0625],...
    'enable' , 'off',...
    'Callback' , @slider3_Callback,...
    'Position',[240 280 400 30]);
```

```
text6_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[40 270 160 60],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'b',...
    'String' , '');
text7_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[680 270 160 60],...
    'Backgroundcolor','w',...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'r',...
    'String' , '');
text8_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[245 310 390 20],...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', [0.7 0.7 0.7],...
    'String' , '9   8   7   6   5   4   3   2   |   2   3   4   5   6   7
8   9');
text9_3 = uicontrol(...
    'Parent', panel3h,...
    'Position',[430 250 20 20],...
    'Style', 'text','FontSize', 10,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'backgroundColor', 'w',...
    'String' , '1');
criteria1_3   = uicontrol(....
    'Parent', panel3h,'Style','listbox',...
    'Callback', @criteria1_Callback_3,...
    'backgroundcolor', 'w',...
    'Value',1,'Position',[200 380 200 150]...
    );
criteria2_3   = uicontrol(....
    'Parent', panel3h,'Style','listbox',...
    'Callback', @criteria2_Callback_3,...
    'backgroundcolor', 'w',...
    'Value',1,'Position',[480 380 200 150]...
    );
popup_3   = uicontrol(....
    'Parent', panel3h,'Style','popup',...
    'String',main_criteria,...
    'Callback', @popup2_Callback,...
    'backgroundcolor', 'w',...
    'Value',1,'Position',[40 380 130 150]...
    );

table4h   = uitable(...
    'Parent',panel4h,'Position',[40 40 800 200],...
    'Columnwidth', 'auto',...
    'Columnformat', [char char char char char char char char]...
    );
```

```
bttn1_4 = uicontrol(...
    'Style','Radio','String','Main Criteria',...
    'position',[40 500 100 30],'parent',panel4h,...
    'Callback', @bttn1_4_Callback,...
    'Value', 0 ...
    );

bttn2_4 = uicontrol(...
    'Style','Radio','String','Sub Criteria',...
    'position',[40 470 100 30],'parent',panel4h,...
    'Callback', @bttn2_4_Callback,...
    'Value', 0 ...
    );

criteria1_4    = uicontrol(....
    'Parent', panel4h,'Style','listbox',...
    'Callback', @criteria1_Callback_4,...
    'backgroundcolor', 'w', 'Visible', 'Off',...
    'Value',1,'Position',[200 380 200 150]...
    );

criteria2_4    = uicontrol(....
    'Parent', panel4h,'Style','listbox',...
    'Callback', @criteria2_Callback_4,...
    'backgroundcolor', 'w','Visible', 'On',...
    'Value',1,'Position',[450 380 150 150]...
    );
criteria3_4    = uicontrol(....
    'Parent', panel4h,'Style','listbox',...
    'Callback', @criteria3_Callback_4,...
    'backgroundcolor', 'w','Visible', 'On',...
    'Value',1,'Position',[650 380 150 150]...
    );
criteria4_4    = uicontrol(....
    'Parent', panel4h,'Style','listbox',...
    'Callback', @criteria4_Callback_4,...
    'backgroundcolor', 'w','Visible', 'Off',...
    'Value',1,'Position',[200 380 200 150]...
    );
slider4h  =  uicontrol(panel4h,'Style','slider',...
    'Max',8,'Min',-8,'Value',0,...
    'SliderStep',[0.0625 0.0625],...
    'enable' , 'off',...
    'Callback' , @slider4_Callback,...
    'Position',[240 280 400 30]);

popup_4    = uicontrol(....
    'Parent', panel4h,'Style','popup',...
    'Callback', @popup4_Callback,'String', main_criteria,...
    'backgroundcolor', 'w','Enable', 'Off',...
    'Value',1,'Position',[40 300 130 150]...
    );

text8_4 = uicontrol(...
    'Parent', panel4h,...
    'Position',[245 310 390 20],...
    'Min', 1, 'Max' , 3,...
    'Style', 'text','FontSize', 12,...
    'Fontweight', 'bold',...
    'ForegroundColor', [0.7 0.7 0.7],...
```

```
    'String' , '9   8   7   6   5   4   3   2   |   2   3   4   5   6   7
8   9');

text9_4 = uicontrol(...
    'Parent', panel4h,...
    'Position',[430 250 20 20],...
    'Style', 'text','FontSize', 10,...
    'Fontweight', 'bold',...
    'ForegroundColor', 'black',...
    'backgroundColor', 'w',...
    'String' , '1');

save_bttn = uicontrol('Style','pushbutton','String','Save',...
    'Position',[255,50,70,25],'Parent', panel1h,...
    'Callback',{@save_bttn_Callback});
load_bttn = uicontrol('Style','pushbutton','String','Load',...
    'Position',[345,50,70,25],'Parent', panel1h,...
    'Callback',{@load_bttn_Callback});

criteria1_5   = uicontrol(....
    'Parent', panel5h,'Style','listbox',...
    'String',main_criteria,...
    'Callback', @criteria1_5_Callback,...
    'backgroundcolor', 'w',...
    'visible','off',...
    'Value',1,'Position',[100 350 300 200]...
    );

cal_bttn = uicontrol('Style','pushbutton','String','Calculate',...
    'Position',[340,50,100,25],'Parent', panel5h,...
    'Callback',{@cal_bttn_Callback});

table5h   = uitable(...
    'Parent',panel5h,'Position',[150 120 600 180],...
    'Columnwidth', 'auto',...
    'Columnformat', [char char char char char char char char]...
    );
dis_bttn = uicontrol('Style','pushbutton','String','Final Result',...
    'Position',[460,50,100,25],'Parent', panel5h,'Visible','Off',...
    'Callback',{@dis_bttn_Callback});
sub_bttn = uicontrol('Style','pushbutton','String','Criteria Result',...
    'Position',[460,50,100,25],'Parent', panel5h,'Visible','Off',...
    'Callback',{@sub_bttn_Callback});
ah1 = axes('Parent',panel5h,'units','pixels',...
          'Position',[570 350 250 200],'Visible','off');
ah2 = axes('Parent',panel5h,'units','pixels',...
          'Position',[150 350 250 200],'Visible','off');
 htext2 = text('Parent',ah2);
    function text2_Callback(hObject,eventdata)

    end
    function criteria_Callback(hObject,eventdata)
        index_selected = get(hObject,'Value');
        set(subcriteriah,'String',subcriteria_cell(:,index_selected))
    end
    function listbox2_Callback(hObject,eventdata)
    end
    function slider_Callback(hObject,eventdata)
```

```
        current_value = get(sliderh, 'Value');
        actual_value = abs(round(current_value))+1;
        set(text9, 'String', round(actual_value));
        a = get(criteria1, 'Value');
        b = get(criteria2, 'Value');
        if (a<=b)
            b = b+1;
        else
            b=b;
        end
        if round(current_value)<0
            set (text9, 'ForegroundColor','b')
            data(a,b,1) = {actual_value};
            data(b,a,1) = {1/actual_value};

        else
            set (text9, 'ForegroundColor','r')
            data(b,a,1) = {actual_value};
            data(a,b,1) = {1/actual_value};
        end
        set(tableh, 'Data', cell2mat([data(:,:,1,1) ahp_data(:,1)]));
        dataarray = cell2mat (data(:,:,1,1));
        check = min(dataarray);
        minimum_check = min(check);
        if (minimum_check ~=0)
            data1 = data(:,:,1,1);
            data2=cell2mat(data1);
            average = sum(data2);
            x=1;
            while x <= size(data2)
                data3(:,x) = data2(:,x)/average(x);
                x = x+1;
            end
            %disp(sum(data3(1,:)));
            x = 1;
            while x <= size(data3)
                ahp(x,1) = sum(data3(x,:))/length(data3);
                ahp_data(x,1) = {ahp(x,1)};
                x = x+1;
            end

            set(tableh, 'Data', cell2mat([data(:,:,1,1) ahp_data(:,1)]));

            %disp(average*ahp);

            eigen_value =max(eig(dataarray));%average*ahp; %;
            consistency_index = (eigen_value - length(dataarray)) /
(length(dataarray)-1);
            if length(dataarray) < 3
                CR = 0;
            elseif length(dataarray) == 3
                CR = consistency_index/0.58;
            elseif length(dataarray) == 4
                CR = consistency_index/0.9;
            elseif length(dataarray) == 5
                CR = consistency_index/1.12;
            elseif length(dataarray) == 6
                CR = consistency_index/1.24;
            elseif length(dataarray) == 7
```

```
            CR = consistency_index/1.32;
        elseif length(dataarray) == 8
            CR = consistency_index/1.41;
        elseif length(dataarray) == 9
            CR = consistency_index/1.45;
        else
            CR = consistency_index/1.49;
        end
        if CR > 0.1
            set (text_CI2, 'String', CR, 'ForegroundColor', 'r');
        else
            set (text_CI2, 'String', CR,'ForegroundColor', 'black');
        end
    else
    end


end
function criteria1_Callback(hObject,eventdata)
    set(sliderh, 'Value', 0,'enable','on');
    set(text9, 'String', 1,'Foregroundcolor' , 'black');
    index_selected = get(hObject,'Value');
    list = get(hObject,'String');
    p = 1;
    q = 1;
    while (p <= max(main_size))
        if p == index_selected;
        elseif p > index_selected;
            list1(q,1) = list(p,1);
            q = q+1;
        else
            list1(q,1) = list(p,1);
            q = q+1;
        end
        p = p+1;
    end
    set(criteria2, 'String', list1, 'Value', 1);
    set(text6, 'String', list(index_selected));
    list2 = get(criteria2, 'String');

    if index_selected ~= max(size(list))
        set(text7, 'String', list2(1,1));
    else
        set(text7, 'String', '')
    end
end
function criteria2_Callback(hObject,eventdata)
    set(sliderh, 'Value', 0);
    set(text9, 'String', 1, 'Foregroundcolor' , 'black');
    index_selected_1 = get(hObject,'Value');
    list_2 = get(hObject, 'String');
    set(text7, 'String', list_2(index_selected_1 ));
end
function popup2_Callback(hObject,eventdata)
    popup_value = get(popup_3, 'Value');
    set(criteria1_3, 'String', subcriteria_cell(:,popup_value));
    c = get(popup_3,'Value');
    x=1;
    while x<=sub_size(c);
    sub_buff(x) = subcriteria_cell(x,c);
```

```
        x=x+1;
        end
        sub_buff1=sub_buff;
        sub_buff(x) = {'AHP Weight'};
        set(table3h, 'Data', [cell2mat(data(:,:,c+1,1))
cell2mat(ahp_data(:,:,c+1,1))],...
            'ColumnName',sub_buff,'RowName' , sub_buff1);
    end
    function criteria1_Callback_3(hObject,eventdata)
        set(slider3h, 'Value', 0,'enable','on');
        set(text9_3, 'String', 1,'Foregroundcolor' , 'black');
        index_selected = get(hObject,'Value');
        list_3 = get(hObject,'String');
        p = 1;
        q = 1;
        main_criteria_value = get(popup_3,'Value');
        while (p <= subcriteriacell_size(main_criteria_value))
            if p == index_selected;
            elseif p > index_selected;
                list1_3(q,1) = list_3(p,1);
                q = q+1;
            else
                list1_3(q,1) = list_3(p,1);
                q = q+1;
            end
            p = p+1;
        end
        set(criteria2_3, 'String', list1_3, 'Value', 1);
        set(text6_3, 'String', list_3(index_selected));
        list2_3 = get(criteria2_3, 'String');

        if index_selected ~= max(size(list_3))
            set(text7_3, 'String', list2_3(1,1));
        else
            set(text7_3, 'String', '')
        end
    end
    function slider3_Callback(hObject,eventdata)

        current_value = get(hObject, 'Value');
        actual_value = abs(round(current_value))+1;
        set(text9_3, 'String', round(actual_value));
        a = get(criteria1_3, 'Value');
        b = get(criteria2_3, 'Value');
        c = get(popup_3,'Value');

        if (a<=b)
            b = b+1;
        else
            b=b;
        end
        if round(current_value)<0
            set (text9_3, 'ForegroundColor','b');
            data(a,b,c+1,1) = {actual_value};
            data(b,a,c+1,1) = {1/actual_value};

        else
            set (text9_3, 'ForegroundColor','r');
            data(b,a,c+1,1) = {actual_value};
            data(a,b,c+1,1) = {1/actual_value};
```

```
        end
        dataarray = cell2mat(data(:,:,c+1,1));
        check = min(dataarray);
        minimum_check = min(check);

        %display(minimum_check);
        %clc;
        %display(data);
        set (table3h,'Data',data(:,:,c+1,1));

        if (minimum_check ~=0)
            data1 = data(:,:,c+1,1);
            data2=cell2mat(data1);
            average = sum(data2);
            x=1;
            while x <= size(data2)
                data3(:,x) = data2(:,x)/average(x);
                x = x+1;
            end
            %disp(sum(data3(1,:)));
            x = 1;
            while x <= size(data3)
                ahp_data(x,1,c+1,1) = {sum(data3(x,:))/length(data3)};
                x = x+1;
            end
            set(table3h, 'Data', cell2mat([data(:,:,c+1,1)
ahp_data(:,1,c+1,1)]));
            disp(data(:,:,c+1,1));
            disp(ahp_data(:,1,c+1,1));
            eigen_value = max(eig(dataarray));
            consistency_index = (eigen_value - length(dataarray)) /
(length(dataarray)-1);

            if length(dataarray) < 3
                CR = 0;
            elseif length(dataarray) == 3
                CR = consistency_index/0.58;
            elseif length(dataarray) == 4
                CR = consistency_index/0.9;
            elseif length(dataarray) == 5
                CR = consistency_index/1.12;
            elseif length(dataarray) == 6
                CR = consistency_index/1.24;
            elseif length(dataarray) == 7
                CR = consistency_index/1.32;
            elseif length(dataarray) == 8
                CR = consistency_index/1.41;
            elseif length(dataarray) == 9
                CR = consistency_index/1.45;
            else
                CR = consistency_index/1.49;
            end
            if CR > 0.1
                set (text_CI2_3, 'String', CR, 'ForegroundColor', 'r');
            else
                set (text_CI2_3, 'String', CR,'ForegroundColor', 'black');
            end

        else
```

```
    end

end
function criteria2_Callback_3(hObject,eventdata)
    set(slider3h, 'Value', 0);

    set(text9_3, 'String', 1, 'Foregroundcolor' , 'black');
    index_selected_1_3 = get(hObject,'Value');
    list_2_3 = get(hObject, 'String');
    set(text7_3, 'String', list_2_3(index_selected_1_3 ));

end
function bttn1_4_Callback(hObject,eventdata)
    set (bttn2_4, 'Value', 0);
    set (bttn1_4, 'Value', 1);
    set (criteria1_4, 'Visible', 'On', 'String', main_criteria)
    set (criteria4_4, 'Visible', 'Off')
    %          set (criteria2_4, 'Visible', 'On')
    set (popup_4, 'Enable', 'Off')
    set (criteria2_4, 'String', '');
    set(table4h, 'Data','');
end
function bttn2_4_Callback(hObject,eventdata)
    set (bttn1_4, 'Value', 0);
    set (bttn2_4, 'Value', 1);
    set (criteria1_4, 'Visible', 'Off');

    %          set (criteria2_4, 'Visible', 'On')
    set (popup_4, 'Enable', 'On', 'Value', 1)
    set (criteria2_4, 'String', '');
    set(table4h, 'Data','');
end
function criteria1_Callback_4(hObject,eventdata)

    set (criteria2_4, 'String', alternatives);
    bttnvalue = get (bttn1_4, 'Value');
    criteria_value = get(criteria1_4, 'Value');
    set(table4h, 'Data', data(:,:,criteria_value,bttnvalue+1),...
        'ColumnName',alternatives,'RowName' , alternatives);
end
function criteria2_Callback_4(hObject,eventdata)
    index_selected_4 = get(hObject,'Value');
    list_alt = get(hObject,'String');

    p = 1;
    q = 1;
    alt_value = get(criteria2_4,'Value');
    %display(subcriteriacell_size(main_criteria_value));
    while (p <= alter_size)
        if p == index_selected_4;
        elseif p > index_selected_4;
            list_4_4(q,1) = list_alt(p,1);
            q = q+1;
        else
            list_4_4(q,1) = list_alt(p,1);
            q = q+1;
        end
        p = p+1;
    end
    set(criteria3_4, 'String', list_4_4, 'Value', 1);
```

```
        %set(text6_3, 'String', list_3(index_selected));
        %list2_3 = get(criteria2_3, 'String');

        % if index_selected ~= max(size(list_3))
        %     set(text7_3, 'String', list2_3(1,1));
        %else
        %    set(text7_3, 'String', '')
        %end

    end
    function criteria3_Callback_4(hObject,eventdata)
        set (slider4h, 'Value', 0,'enable','on');

    end
    function criteria4_Callback_4(hObject,eventdata)
        subcriteria_value = get(criteria4_4, 'Value');
        subcriteria_value_2 = get(popup_4, 'Value');
        x=1;
        while x<=alter_size;
            alter_buff(x) = alternatives(x);
            x=x+1;
        end
        alter_buff(x) = {'AHP Weight'};
        set(table4h, 'Data',
cell2mat([data(:,:,subcriteria_value,subcriteria_value_2+2)
ahp_data(:,:,subcriteria_value,subcriteria_value_2+2)]),...
            'ColumnName',alter_buff ,'RowName' , alternatives);
    end
    function slider4_Callback(hObject,eventdata)
        current_value = get(hObject, 'Value');
        actual_value = abs(round(current_value))+1;
        set(text9_4, 'String', round(actual_value));

        a = get(criteria2_4, 'Value');
        b = get(criteria3_4, 'Value');
        c = get(popup_4,'Value');
        e = get(bttn2_4, 'Value');
        f = get(bttn1_4, 'Value');
        g = get(criteria4_4, 'Value');
        h = get(criteria1_4, 'Value');

        if (f == 1)
            if (a<=b)
                b = b+1;
            else
                b=b;
            end

            if round(current_value)<0
                set (text9_4, 'ForegroundColor','b')
                data(a,b,h,2) = {actual_value};
                data(b,a,h,2) = {1/actual_value};

            else
                set (text9_4, 'ForegroundColor','r')
                data(b,a,h,2) = {actual_value};
                data(a,b,h,2) = {1/actual_value};
            end
            set(table4h, 'Data', data(:,:,h,2));
            dataarray = cell2mat (data(:,:,h,2));
```

```
            check = min(dataarray);
            minimum_check = min(check);
            old_row = length(data(:,:,h,2));
            %disp(old_row);
            if (minimum_check ~=0)
                data1 = data(:,:,h,2);
                data2=cell2mat(data1);
                average = sum(data2);

                row_name = (get(table4h,'RowName'));
                row_size = length(row_name);
                if row_size<=old_row-1
                    row_name(row_size+1,:) = {'Column Total'};
                    col_name = (get(table4h,'ColumnName'));
                    col_size = length(col_name);
                    col_name(col_size+1,:) = {'AHP Weights'};
                    set
(table4h,'RowName',row_name,'ColumnName',col_name);
                else
                end

                x=1;
                while x <= size(data2)
                    data3(:,x) = data2(:,x)/average(x);
                    x = x+1;
                end
                %disp(sum(data3(1,:)));
                x = 1;
                while x <= size(data3)
                    ahp_data(x,1,h,2) = {(sum(data3(x,:))/length(data3))};
                    x = x+1;
                end

                %disp(average*ahp);

                eigen_value = max(eig(dataarray));
                consistency_index = (eigen_value - length(dataarray)) /
(length(dataarray)-1);
                if length(dataarray) < 3
                    CR = 0;
                elseif length(dataarray) == 3
                    CR = consistency_index/0.58;
                elseif length(dataarray) == 4
                    CR = consistency_index/0.9;
                elseif length(dataarray) == 5
                    CR = consistency_index/1.12;
                elseif length(dataarray) == 6
                    CR = consistency_index/1.24;
                elseif length(dataarray) == 7
                    CR = consistency_index/1.32;
                elseif length(dataarray) == 8
                    CR = consistency_index/1.41;
                elseif length(dataarray) == 9
                    CR = consistency_index/1.45;
                else
                    CR = consistency_index/1.49;
                end
                if CR > 0.1
                    set (text_CI2_4, 'String', CR, 'ForegroundColor',
'r');
```

```
                else
                    set (text_CI2_4, 'String', CR,'ForegroundColor',
'black');
                end
                set(table4h, 'Data', cell2mat([data(:,:,h,2)
ahp_data(:,1,h,2)]));
            else
            end

        else
            if (a<=b)
                b = b+1;
            else
                b=b;
            end

            if round(current_value)<0
                set (text9_4, 'ForegroundColor','b')
                data(a,b,g,c+2) = {actual_value};
                data(b,a,g,c+2) = {1/actual_value};
            else
                set (text9_4, 'ForegroundColor','r')
                data(b,a,g,c+2) = {actual_value};
                data(a,b,g,c+2) = {1/actual_value};
            end
            dataarray = cell2mat (data(:,:,g,c+2));
            check = min(dataarray);
            minimum_check = min(check);
            old_row = length(data(:,:,g,c+2));
            %disp(old_row);
            set (table4h,'Data',data(:,:,g,c+2));

            if (minimum_check ~=0)
                data1 = data(:,:,g,c+2);
                data2=cell2mat(data1);
                average = sum(data2);

                row_name = (get(table4h,'RowName'));
                row_size = length(row_name);
                if row_size<=old_row-1
                    row_name(row_size+1,:) = {'Column Total'};
                    col_name = (get(table4h,'ColumnName'));
                    col_size = length(col_name);
                    col_name(col_size+1,:) = {'AHP Weights'};
                    set
(table4h,'RowName',row_name,'ColumnName',col_name);
                else
                end

                x=1;
                while x <= size(data2)
                    data3(:,x) = data2(:,x)/average(x);
                    x = x+1;
                end
                %disp(sum(data3(1,:)));
                x = 1;
                while x <= size(data3)
                    ahp_data(x,1,g,c+2) =
{(sum(data3(x,:))/length(data3))};
                    x = x+1;
```

```
                end

                set(table4h, 'Data', cell2mat([data(:,:,g,c+2)
ahp_data(:,1,g,c+2)]));
                eigen_value = max(eig(dataarray));
                consistency_index = (eigen_value - length(dataarray)) /
(length(dataarray)-1);
                if length(dataarray) < 3
                    CR = 0;
                elseif length(dataarray) == 3
                    CR = consistency_index/0.58;
                elseif length(dataarray) == 4
                    CR = consistency_index/0.9;
                elseif length(dataarray) == 5
                    CR = consistency_index/1.12;
                elseif length(dataarray) == 6
                    CR = consistency_index/1.24;
                elseif length(dataarray) == 7
                    CR = consistency_index/1.32;
                elseif length(dataarray) == 8
                    CR = consistency_index/1.41;
                elseif length(dataarray) == 9
                    CR = consistency_index/1.45;
                else
                    CR = consistency_index/1.49;
                end
                if CR > 0.1
                    set (text_CI2_4, 'String', CR, 'ForegroundColor',
'r');
                else
                    set (text_CI2_4, 'String', CR,'ForegroundColor',
'black');
                end
            else
            end
        end

    end
    function save_bttn_Callback(hObject,eventdata)
        disp(ahp_data(:,:,1,1));
        Excel = actxserver ('Excel.Application');
File='C:\Documents and Settings\Boon.BOON-9F4F8D0388\Desktop\ahp1.xlsx';
if ~exist(File,'file')
    ExcelWorkbook = Excel.workbooks.Add;
    ExcelWorkbook.SaveAs(File,1);
    ExcelWorkbook.Close(false);
end
invoke(Excel.Workbooks,'Open',File);



        xlswrite1(File, {'Main Criteria Score'}, 'Data','A1');
        p=2;
        y=1;
        while y <= main_size;
            output_buff(1,y) = {sprintf('Output %d', y)};
            y=y+1;
        end
        output_buff(1,y) = {'AHP Weight'};
        xlswrite1(File, output_buff, 'Data','B2');
```

```
        xlswrite1(File, main_criteria, 'Data','A3');
        xlswrite1(File, [cell2mat(data(:,:,1,1))
cell2mat(ahp_data(:,:,1,1))], 'Data','B3');
        p = 2 + main_size + 1+3;
        xlswrite1(File, {'Sub Criteria Score'}, 'Data',sprintf('A%d', p));

        x = 1;
        while x<=main_size
        buffer = cell2mat(main_criteria(x));
        p = p+1;
        y = 1;
        ch = 65;
        xlswrite1(File, {sprintf('%d. %s', x, buffer)} ,
'Data',sprintf('A%d', p));
        p=p+2;
        while y <= sub_size(x);
            output_buff1(1,y) = {sprintf('Output %d', y)};
            y=y+1;
        end
        output_buff1(1,y) = {'AHP Weight'};
        xlswrite1(File, {sprintf('%s. Comparison of criteria with respect
to %s',char(ch), buffer)}, 'Data',sprintf('A%d', p));
        p = p+1;
        xlswrite1(File, output_buff1, 'Data',sprintf('B%d', p));
        clear output_buff1;
        p=p+1;


        xlswrite1(File, subcriteria(:,x), 'Data',sprintf('A%d', p));
        xlswrite1(File, [cell2mat(data(:,:,x+1,1))
cell2mat(ahp_data(:,:,x+1,1))], 'Data',sprintf('B%d', p));

        p = p + sub_size(1)+3;
        z = 1;
        while(z<=sub_size(x))
            buffer = cell2mat(subcriteria(z,x));
            ch = ch + 1;
            xlswrite1(File, {sprintf('%s. Comparison of Suppliers with
respect to %s',char(ch),buffer )}, 'Data',sprintf('A%d', p));
            p = p+1;
            y=1;
                    while y <= alter_size;
            output_buff2(1,y) = {sprintf('Output %d', y)};
            y=y+1;
        end
        output_buff2(1,y) = {'AHP Weight'};
                xlswrite1(File, output_buff2, 'Data',sprintf('B%d', p));
        clear output_buff2;
        p=p+1;
            xlswrite1(File, alternatives, 'Data',sprintf('A%d', p));
            xlswrite1(File, [cell2mat(data(:,:,z,x+2))
cell2mat(ahp_data(:,:,z,x+2))], 'Data',sprintf('B%d', p));
            p = p + alter_size +3;
            z = z+1;
        end
        x = x+1;
        end
        p = 1;
        x=1;
        xlswrite1(File, main_size, 'Data_raw',sprintf('A%d',p));
```

```
        p=p+1;
        xlswrite1(File, sub_size, 'Data_raw',sprintf('A%d',p));
        p=p+1;
        xlswrite1(File, alter_size, 'Data_raw',sprintf('A%d',p));
        p=p+1;
        xlswrite1(File, [cell2mat(data(:,:,1,1))
cell2mat(ahp_data(:,:,1,1))], 'Data_raw',sprintf('A%d',p));
        p=p+main_size;
        while x<=main_size
            xlswrite1(File, [cell2mat(data(:,:,x+1,1))
cell2mat(ahp_data(:,:,x+1,1))], 'Data_raw',sprintf('A%d',p));
            p=p+sub_size(x);
            y = 1;
            while y<= sub_size(x)
                xlswrite1(File, [cell2mat(data(:,:,y,x+2))
cell2mat(ahp_data(:,:,y,x+2))], 'Data_raw',sprintf('A%d',p));
                p=p+alter_size;
                y = y+1;
            end
            x=x+1;
        end
        x=1;

        while x<=main_size
                xlswrite1(File, ahp_data(1:alter_size,1,1,main_size+2+x),
'Data_raw',sprintf('A%d',p));
                x = x+1;
                p = p+alter_size+1;
        end
        xlswrite1(File, ahp_data(1:alter_size,1,1,2*main_size+3),
'Data_raw',sprintf('A%d',p));
        %xlswrite('ahp.xlsx', data(:,:,1:1), sprintf('%s%d:%s%d',
x,y,z,w));
        %xlswrite('ahp.xlsx', {sprintf('Output %d', x)}, 'A1')
        invoke(Excel.ActiveWorkbook,'Save');
        Excel.Quit
        Excel.delete
        clear Excel
    end
    function load_bttn_Callback(hObject,eventdata)
        Excel = actxserver ('Excel.Application');
        File='C:\Documents and Settings\Boon.BOON-
9F4F8D0388\Desktop\ahp1.xlsx';
        if ~exist(File,'file')
            ExcelWorkbook = Excel.Workbooks.Add;
            ExcelWorkbook.SaveAs(File,1);
            ExcelWorkbook.Close(false);
        end
        Excel.Workbooks.Open(File);

        main_size = xlsread1(File, 'Data_raw','A1');
        char_buff = 65;
        sub_size = xlsread1(File, 'Data_raw',sprintf('A2:%s2',
char(char_buff + main_size-1)));
        alter_size = xlsread1(File, 'Data_raw','A3');
        p = 4;
        temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d','A',p,char(char_buff+main_size-
1),p+main_size-1));
```

```
        ahp_temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d',char(char_buff+main_size),p,char(char_buff
+main_size),p+main_size-1));
        size_temp = size(temp);
        x=1;
        while x<= size_temp(1)
            y=1;
            while y<=size_temp(2)
                data(x,y,1,1)= {temp(x,y)};
                y=y+1;
            end
            if isempty(ahp_temp)~=1
            ahp_data(x,1,1,1)= {ahp_temp(x)};
            else
            end
            x=x+1;
        end
        a = 1;
        p = p+main_size;
        while a <= main_size
        temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d','A',p,char(char_buff+sub_size(a)-
1),p+sub_size(a)-1));
        ahp_temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d',char(char_buff+sub_size(a)),p,char(char_bu
ff+sub_size(a)),p+sub_size(a)-1));
        size_temp = size(temp);
        x=1;
        while x<= size_temp(1)
            y=1;
            while y<=size_temp(2)
                data(x,y,a+1,1)= {temp(x,y)};
                y=y+1;
            end
            if isempty(ahp_temp)~=1
            ahp_data(x,1,a+1,1)= {ahp_temp(x)};
            else
            end
            x=x+1;
        end
        b = 1;
        p = p+sub_size(a);
        while b<=sub_size(a)
        temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d','A',p,char(char_buff+alter_size-
1),p+alter_size-1));
        ahp_temp = xlsread1(File,
'Data_raw',sprintf('%s%d:%s%d',char(char_buff+alter_size),p,char(char_buf
f+alter_size),p+alter_size-1));
        size_temp = size(temp);
        x=1;
        while x<= size_temp(1)
            y=1;
            while y<=size_temp(2)
                data(x,y,b,a+2)= {temp(x,y)};
                y=y+1;
            end
            if isempty(ahp_temp)~=1
            ahp_data(x,1,b,a+2)= {ahp_temp(x)};
            else
            end
```

```
            x=x+1;
        end
        b=b+1;
        p = p+alter_size;
        end

        a=a+1;
        end

        Excel.ActiveWorkbook.Save;
        Excel.Quit
        Excel.delete
        clear Excel



    end
    function popup4_Callback(hObject,eventdata)

        popup_value = 0;
        popup_value = get(popup_4, 'Value');
        set(criteria4_4, 'String', subcriteria_cell(:,popup_value));
        set(table4h, 'Data','');
        set (criteria2_4, 'String', alternatives);
        set (criteria4_4, 'Visible', 'On')
                subcriteria_value = get(criteria4_4, 'Value');
        subcriteria_value_2 = get(popup_4, 'Value');
        x=1;
        while x<=alter_size;
            alter_buff(x) = alternatives(x);
            x=x+1;
        end
        alter_buff(x) = {'AHP Weight'};
        set(table4h, 'Data',
cell2mat([data(:,:,subcriteria_value,subcriteria_value_2+2)
ahp_data(:,:,subcriteria_value,subcriteria_value_2+2)]),...
            'ColumnName',alter_buff ,'RowName' , alternatives);
    end
    function criteria1_5_Callback(hObject,eventdata)
        c=get(criteria1_5,'Value');
        x=1;
        while x<=sub_size(c);
        sub_buff(x) = subcriteria_cell(x,c);
        x=x+1;
        end
        sub_buff1=alternatives;
        sub_buff1(length(alternatives)+1)={'Local Weights'};
        sub_buff(x) = {'AHP Weight'};
        combined_ahp={cell2mat([ahp_data(:,1,1,c+2);
ahp_data(1,1,c+1,1)])};
        y=2;
        while y<=sub_size(c)
            combined_ahp={cell2mat(combined_ahp)
cell2mat([ahp_data(:,1,y,c+2); ahp_data(y,1,c+1,1)])};
            y=y+1;
        end
        set(table5h, 'Data', [cell2mat(combined_ahp)
cell2mat(ahp_data(:,:,1,c+main_size+2))],'ColumnName',sub_buff,'RowName' ,
sub_buff1);
        clear combined_ahp;
```

```
                set(ah2,'Visible','Off');
        set(ah1,'Visible','On');

        y = barh(ah1, cell2mat(ahp_data(1:alter_size,1,1,2+main_size+c)),
'barwidth', .6,'LineWidth', 1,'FaceColor', 'b', 'EdgeColor', 'b');
        xlabel('Weighted Score');
        a = (cell2mat(main_criteria(c)));
        title(ah1,sprintf('AHP Weight Results respect to %s',
a),'FontSize',12,'FontWeight','demi')
        x=1;

        while x<=alter_size
            b= num2str(cell2mat(ahp_data(x,1,1,2+main_size+c)));
            htext = text(0,x,sprintf('
%s',b),'Parent',ah1,'Color','r','FontWeight','demi');

            x=x+1;
        end
        set(ah1,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',alternatives,'xlim',[0 1])

    end

    function cal_bttn_Callback(hObject,eventdata)
        set(criteria1_5,'Visible','On');
        c=get(criteria1_5,'Value');
        x=1;
        while x<=sub_size(c);
        sub_buff(x) = subcriteria_cell(x,c);
        x=x+1;
        end
        sub_buff1=alternatives;
        sub_buff1(length(alternatives)+1)={'Local Weights'};
        sub_buff(x) = {'AHP Weight'};
        set(table5h, 'ColumnName',sub_buff,'RowName' , sub_buff1);

        combined_ahp={cell2mat([ahp_data(:,1,1,c+2);
ahp_data(1,1,c+1,1)])};
        y=2;
        while y<=sub_size(c)
        combined_ahp={cell2mat(combined_ahp)
cell2mat([ahp_data(:,1,y,c+2); ahp_data(y,1,c+1,1)])};
        y=y+1;
        end
        x=1;
        clear combined_ahp;
        while x<=main_size
            y=1;
            while y<=alter_size
                z=1;
                ahp_data(y,1,1,main_size+2+x)={0};
                while z<= sub_size(x)

                    ahp_data(y,1,1,main_size+2+x) =
{cell2mat(ahp_data(y,1,1,main_size+2+x))+
cell2mat(ahp_data(y,1,z,x+2))*cell2mat(ahp_data(z,1,x+1,1))};
                    z=z+1;
                end
                ahp_data(y+1,1,1,main_size+2+x)=
{sum(cell2mat(ahp_data(1:y,1,1,main_size+2+x)))};
```

```
                y=y+1;
            end
           x=x+1;
        end
            y=1;
            while y<=alter_size
                z=1;
                ahp_data(y,1,1,2*main_size+3)={0};
                while z<= main_size
                    ahp_data(y,1,1,2*main_size+3) =
{cell2mat(ahp_data(y,1,1,2*main_size+3))+
cell2mat(ahp_data(y,1,1,main_size+2+z))*cell2mat(ahp_data(z,1,1,1))};
                    z=z+1;
                end
                ahp_data(y+1,1,1,2*main_size+3)=
{sum(cell2mat(ahp_data(1:y,1,1,main_size+2+x)))};
                y=y+1;
            end

        set(dis_bttn,'Visible','On');

        %disp(ahp_data(:,1,1, 9:13))
    end
    function dis_bttn_Callback(hObject,eventdata)
        set(sub_bttn,'Visible','On');
        set(dis_bttn,'Visible','Off');
        set(criteria1_5,'Visible','Off');

        sub_buff = main_criteria;
        sub_buff1=alternatives;
        sub_buff1(length(alternatives)+1)={'Local Weights'};
        sub_buff(main_size+1) = {'AHP Weight'};
        combined_ahp={cell2mat([ahp_data(1:alter_size,1,1,main_size+3);
ahp_data(1,1,1,1)])};
        y=2;
        while y<=main_size
        combined_ahp={cell2mat(combined_ahp)
cell2mat([ahp_data(1:alter_size,1,1,main_size+2+y); ahp_data(y,1,1,1)])};
        y=y+1;
        end
       disp(cell2mat(combined_ahp));
       disp(cell2mat(ahp_data(:,:,1,3+main_size*2)));
        set(table5h, 'Data', [cell2mat(combined_ahp)
cell2mat(ahp_data(:,:,1,3+main_size*2))],'ColumnName',sub_buff,'RowName' ,
sub_buff1);
        clear combined_ahp;
        set(ah2,'Visible','On');
        set(ah1,'Visible','On');
        y = barh(ah1, cell2mat(ahp_data(1:alter_size,1,1,2*main_size+3)),
'barwidth', .6,'LineWidth', 1,'FaceColor', 'b', 'EdgeColor', 'b');

       % bar(cell2mat(ahp_data(1:alter_size,1,1,2*main_size+3)),
'barwidth', .6,'LineWidth', 1,'FaceColor', 'b', 'EdgeColor', 'b');
        xlabel('Weighted Score','Parent',ah1);
        title(ah1,'Final AHP Weight
Results','FontSize',12,'FontWeight','demi')
        x=1;
               while x<=alter_size
           b= num2str(cell2mat(ahp_data(x,1,1,2*main_size+3)));
```

```
            htext = text(0,x,sprintf('
%s',b),'Parent',ah1,'Color','r','FontWeight','demi');
            x=x+1;
                end

        set(ah1,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',alternatives,'xlim',[0 1])


        z = barh(ah2, cell2mat(ahp_data(1:main_size,1,1,1)),
'barwidth', .6,'LineWidth', 1,'FaceColor', 'b', 'EdgeColor', 'b');
        xlabel('Weighted Score');
        title(ah2,'AHP Weight Results respect to Main
Criteria','FontSize',12,'FontWeight','demi')
                        if max(cell2mat(ahp_data(:,1,1,1))) < 0.25;
        set(ah2,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',main_criteria,'xlim',[0 .25])
        elseif max(cell2mat(ahp_data(:,1,1,1))) < 0.5;
        set(ah2,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',main_criteria,'xlim',[0 .5])
        elseif max(cell2mat(ahp_data(:,1,1,1))) < 0.75;
        set(ah2,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',main_criteria,'xlim',[0 .75])
        else
        set(ah2,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',main_criteria,'xlim',[0 .1])
        end

        x=1;
        while x<=main_size
            b= num2str(cell2mat(ahp_data(x,1,1,1)));
            htext2 = text(0,x,sprintf('
%s',b),'Parent',ah2,'Color','r','FontWeight','demi');
            x=x+1;
        end


    end
    function sub_bttn_Callback(hObject,eventdata)
        set(dis_bttn,'Visible','On');
        set(sub_bttn,'Visible','Off');
        set(criteria1_5,'Visible','On');
        c=get(criteria1_5,'Value');
        set(ah2,'Visible','Off');
        set(ah1,'Visible','On');

        y = barh(ah1, cell2mat(ahp_data(1:alter_size,1,1,2+main_size+c)),
'barwidth', .6,'LineWidth', 1,'FaceColor', 'b', 'EdgeColor', 'b');
        xlabel('Weighted Score');
        a = (cell2mat(main_criteria(c)));
        title(ah1,sprintf('AHP Weight Results respect to %s',
a),'FontSize',12,'FontWeight','demi')
        x=1;

        while x<=alter_size
            b= num2str(cell2mat(ahp_data(x,1,1,2+main_size+c)));
            htext = text(0,x,sprintf('
%s',b),'Parent',ah1,'Color','r','FontWeight','demi');
```

```
            x=x+1;
        end
        set(ah1,'xtick', [0 0.2 0.4 0.6 0.8
1],'yticklabel',alternatives,'xlim',[0 1])

    end
    function toggletab1_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'on')
        set (panel2h, 'Visible', 'off')
        set (panel3h, 'Visible', 'off')
        set (panel4h, 'Visible', 'off')
        set (panel5h, 'Visible', 'off')
        set (panel6h, 'Visible', 'off')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab2, 'backgroundcolor', select_color)
        set (toggletab3, 'backgroundcolor', select_color)
        set (toggletab4, 'backgroundcolor', select_color)
        set (toggletab5, 'backgroundcolor', select_color)
        set (toggletab6, 'backgroundcolor', select_color)

    end
    function toggletab2_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'off')
        set (panel2h, 'Visible', 'on')
        set (panel3h, 'Visible', 'off')
        set (panel4h, 'Visible', 'off')
        set (panel5h, 'Visible', 'off')
        set (panel6h, 'Visible', 'off')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab1, 'backgroundcolor', select_color)
        set (toggletab3, 'backgroundcolor', select_color)
        set (toggletab4, 'backgroundcolor', select_color)
        set (toggletab5, 'backgroundcolor', select_color)
        set (toggletab6, 'backgroundcolor', select_color)
        set (tableh,'Data',[data(:,:,1,1) ahp_data(:,:,1,1)]);
    end
    function toggletab3_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'off')
        set (panel2h, 'Visible', 'off')
        set (panel3h, 'Visible', 'on')
        set (panel4h, 'Visible', 'off')
        set (panel5h, 'Visible', 'off')
        set (panel6h, 'Visible', 'off')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab2, 'backgroundcolor', select_color)
        set (toggletab1, 'backgroundcolor', select_color)
        set (toggletab4, 'backgroundcolor', select_color)
        set (toggletab5, 'backgroundcolor', select_color)
        set (toggletab6, 'backgroundcolor', select_color)

    end
    function toggletab4_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'off')
        set (panel2h, 'Visible', 'off')
        set (panel3h, 'Visible', 'off')
        set (panel4h, 'Visible', 'on')
        set (panel5h, 'Visible', 'off')
        set (panel6h, 'Visible', 'off')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab2, 'backgroundcolor', select_color)
```

```
        set (toggletab3, 'backgroundcolor', select_color)
        set (toggletab1, 'backgroundcolor', select_color)
        set (toggletab5, 'backgroundcolor', select_color)
        set (toggletab6, 'backgroundcolor', select_color)
    end
    function toggletab5_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'off')
        set (panel2h, 'Visible', 'off')
        set (panel3h, 'Visible', 'off')
        set (panel4h, 'Visible', 'off')
        set (panel5h, 'Visible', 'on')
        set (panel6h, 'Visible', 'off')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab2, 'backgroundcolor', select_color)
        set (toggletab3, 'backgroundcolor', select_color)
        set (toggletab4, 'backgroundcolor', select_color)
        set (toggletab1, 'backgroundcolor', select_color)
        set (toggletab6, 'backgroundcolor', select_color)

    end
    function toggletab6_Callback(hObject,eventdata)
        set (panel1h, 'Visible', 'off')
        set (panel2h, 'Visible', 'off')
        set (panel3h, 'Visible', 'off')
        set (panel4h, 'Visible', 'off')
        set (panel5h, 'Visible', 'off')
        set (panel6h, 'Visible', 'on')
        set (hObject, 'backgroundcolor', default_color)
        set (toggletab2, 'backgroundcolor', select_color)
        set (toggletab3, 'backgroundcolor', select_color)
        set (toggletab4, 'backgroundcolor', select_color)
        set (toggletab5, 'backgroundcolor', select_color)
        set (toggletab1, 'backgroundcolor', select_color)

    end

end
```