MODELLING INDUSTRIAL SYSTEMS: SUSTAINABILITY, COMPLEXITY AND EVOLUTIONARY PROCESSES

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James Scott Baldwin

Advanced Manufacturing Research Centre with Boeing
Department of Mechanical Engineering

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ABSTRACT

New ideas, concepts and understanding that are currently emerging from the science of complex systems are beginning to challenge the way people think about and model industrial systems. In addition, sustainable development and industrial ecology are now two of the most popular concepts with which to understand and represent sustainable industrial systems. In bringing all three of these areas of research together and with a specific focus on the industrial region of Sheffield and South Yorkshire, two theoretical models of sustainable systems are developed with an underlying argument of homology rather than the typical analogy. The aim is to reconcile understanding, in physics, biology, ecology, and the industrial process. Hypotheses of homology are tested on the emergent patterns found in both natural and industrial systems - patterns in energy intensities, production and recycling, diversification, organisational life histories and selection pressures, and systemic stability. The model is then used to examine regional decline and sustainable industrial regeneration in the South Yorkshire region of the UK.

Building on these models, the cladistic evolution of manufacturing technologies and practices is modelled through simulation. Manufacturing cladistics was first developed not only as a means of classifying manufacturing organisations but also, and perhaps more importantly, as a tool to both help deal with change, and use as a guide for organisational re-engineering. However, this approach has one major limitation – it is only a description of the past; the future is not represented. Uncertainty in decision-making and unknown barriers are thought to be major inhibitors behind the introduction of important innovations in technical, organisational and social domains. This thesis reports on the results of a study that interprets two complimentary, but currently unrelated, areas of research, manufacturing cladistics and evolutionary systems methodology. This new framework enables the exploration of evolutionary processes involved in the interactions of technologies and practices, facilitating decision-making as well as the exploration of new organisational structures.

PUBLICATIONS AND CONFERENCE PAPERS EMANATING FROM THIS RESEARCH

Baldwin, J. S., Murray, R., Winder, B. and Ridgway, K. (2004). "A Non-Equilibrium Thermodynamic Model of Industrial Development: Analogy or Homology?" Journal of Cleaner Production 'Applications in Industrial Ecology'. In press.

Baldwin, J. S. Allen, P. M. Winder, B. and Ridgway, K. (2003). "Simulating the Cladistic Evolution of Manufacturing." Accepted for publication in Innovation: Management, Policy and Practice, 5(2-3), 144-155.

Baldwin, J. S. Ridgway, K. Winder, B. and Murray, R. (2004). "Modelling Industrial Ecosystems and the 'Problem' of Evolution." Progress in Industrial Ecology. In press.

Baldwin, J. S. Allen, P. M. Winder, B. and Ridgway, K. (2004). "Modelling Manufacturing Evolution: Thoughts of Sustainable Industrial Development." To be published in the Journal of Cleaner Production.

Baldwin, J. S. Allen, P. M. Winder, B. and Ridgway, K. (2004). "Simulating the Complex Cladistic Evolution of Manufacturing: A Tool for Sustainable Re-Engineering?" Paper presented at ASEAT Conference, Manchester, 7-9th April.

McGlade, J., Murray, R., Baldwin, J. S., Winder, B and Ridgway, K. (2003). "A Co-Evolutionary Framework for Understanding Transformation and Resilience in Industrial and Societal Systems: The Example of South Yorkshire Mining Communities." Paper presented at Industrial Ecology Conference, Manchester, UK, 17-18th June.

Allen, P. M., Strathern, M. and Baldwin, J. (2003) "Understanding Social and Economic Systems as Evolutionary Complex Systems" Paper presented at Uncertainty Conference at Red McCombs School of Business, The University of Texas at Austin, USA, 10-12 April. To appear in book of proceedings and in the Emergence Journal.

Allen, P. M., Strathern, M. and Baldwin, J. (2003) "Computational Social Science: Modelling Evolution and Emergence in Social Systems". Paper presented at Inaugural Conference on Computational Social Sciences at George Mason University, Fairfax, USA, 23-24 May. To appear in the Proceedings of the National Academy of Science, USA.

Allen, P. M., Strathern, M. and Baldwin, J. (2003) "Complexity and the Limits to Learning." Paper presented at Inaugural Conference of NAACSOS, Carnegie Mellon University, Pittsburgh, USA, June 22-25. To be submitted to the Journal of Computational Mathematical Organisational Theory.

Allen, P. M., Rose-Anderssen, C., Strathern, M. and Baldwin, J. (2003) "Complexity: The Evolution of Strategy and Structure" Paper presented at "New Approaches to Strategic Management" University of Lecce Conference, Ostuni, Brindisi, Italy 11-13 September. To appear in the Long Range Planning Journal.

Allen, P. M., Baldwin, J. and Strathern, M. (2003) "Evolution and Creativity and Organisational Change" Paper presented at Complexity, Ethics and Creativity Conference at the London School of Economics, September 17-18. To appear in the Complexity Journal.

TABLE OF CONTENTS

FIGURE LIST

TABLE LIST

CHAPTER 1 - INTRODUCTION

1. Introduction

New concepts and ideas emerging from the science of complex systems, which challenge the established scientific mechanical paradigm of reductionism, are providing new understanding of the relation between natural and anthropogenic systems and the evolutionary processes involved. This understanding also has the potential to provide a framework with which sustainable systems can begin to be understood and represented. As such this thesis, in its exploration and application of these new ideas, also aims to offer a practical contribution to the ongoing regional regeneration effort in South Yorkshire by examining the industrial process at both the level of regional networks of organisations and the level of individual organisations in terms of technologies and practices, and management decision-making. The two levels of analysis are intended to be complimentary as it is impossible to fully understand the activity at the level of the region without investigating the activity of individuals and their decisions, and vice versa.

1.1. Research Aims

The broadest aim of this thesis is to identify issues concerning the sustainability of industrial systems and to determine if new ideas from the science of complex systems can help deepen the understanding of sustainable industrial development and regeneration. The specific research aims of this thesis are:

1. To develop a theoretical model of sustainable complex systems explaining how systems arise, why they arise, and how functions are optimised and then sustained
2. To develop a theoretical model that creates a framework within which evolutionary industrial networks can be represented and understood
3. To extend the debate in industrial ecology beyond the metaphor and the typical focus of industrial ecology models
4. To generate, through modelling, guidelines with which regional/national policy- and decision-makers can follow

5. To build on and interpret two complimentary but currently unrelated areas of research – manufacturing cladistics and evolutionary systems modelling
6. To explore through simulation the interaction of an organisation's different technologies and practices, and investigate the effects of introducing new technologies and practices
7. To demonstrate the usefulness of this new evolutionary framework in terms of both evolving industrial structures and exploring future trajectories that manufacturing can take.

1.2. Thesis Organisation and Structure

The thesis starts in chapter 2 with a review of the literature concerning the concept of sustainable development including definitions, global and national problems spanning environmental, social and economic spheres, and a summary of progress and strategies that have been devised to date. Industrial ecology is identified as the leading concept with which to understand and represent the transitions needed for the sustainability of the industrial process. Therefore the chapter fully explores this concept in terms of definitions, models, case studies, problems and issues, and directions that further research can take.

One direction that the thesis takes is the development of theoretical industrial ecology models, which extend the debate on the ecological metaphor through the use of complex systems thinking, and incorporates other phenomena associated with ecosystem development. This modelling, which analyses sustainable development at the level of the industrial region, is the subject of the first part of the thesis.

The two theoretical models are developed using a framework derived from the new understanding in complex systems thinking. Both models include a review of the appropriate complex systems thinking literature as they are developed. The first model, the subject of chapter 3, is concerned with the sustainability of complex systems in general and applied to most living and meta-living systems either natural or anthropogenic. After a review of the literature concerning Newtonian mechanics, the four laws of thermodynamics, the entropy principle, and contemporary thinking of complex systems, the model provides arguments as to how complex systems arise, why they arise, how the maximum effectiveness of function is reached and how the systems sustains its function. This model satisfies the first research aim of the thesis (see section 1.1), whilst also providing a platform for the third research aim to take IE beyond the metaphor.

The second model, presented in chapter 4, focuses on industrial systems and is an extended industrial ecology model satisfying the second and third research aims. The industrial history of South Yorkshire is taken as the specific case study as the metals-manufacturing system is one of the oldest industrial ecosystems. The case study also allows for a more specific model of an industrial region. The historical re-interpretation of South Yorkshire focuses on several aspects such as initial conditions, major trajectories of development, the major events that helped shape the evolutionary processes and the present composition and structure of the industry. The model then extends the typical IE model, which limits the focus to just material recycling, to include other ecosystem development phenomena such as energy transitions, diversification, life-histories, and climax. These phenomena are taken as hypotheses (5 hypotheses in total) and are tested and supported through the analysis of empirical data from existing databases and the industrial history of South Yorkshire.

To achieve the fourth research aim, policy implications concerning regional decline and regeneration are then discussed and further areas of research identified including the need to study the activity of individual organisations and the decisions that are made at this level. That is, the aim is to use the N-ET model to develop complimentary novel classification schemes and 'blueprints' for organisational change initiatives. The sustainable development of regional economic systems are a manifestation or an emergent phenomenon resulting from the decisions that are made at the level of individual actors and the consequent changes seen at the level of the organisation.

With this and the fifth research aim in mind, the remainder of the thesis investigates the evolutionary processes at the level of individual companies and the decisions that are made. Chapter 5 is an assessment of the utility of manufacturing cladistics, an evolutionary classification scheme, for industrial regeneration, for sustainability and for the future evolution of manufacturing. Following on from the previous models, the most appealing features of manufacturing cladistics are that the approach applies biological classification techniques and that its main emphasis is on the evolution of individual organisations. The assessment covers the literature on biological taxonomic principles, including numerical taxonomy, biological classifications, notions of classifications, and classification schools of thought such as cladistics, other evolutionary classifications, and functional classifications. The chapter then reviews recent applied research on manufacturing cladistics, which includes classifications of manufacturing complexity, management techniques, the hand-tool industry and the evolution of automotive assembly plants.

At this point in the research, the original research aim is to develop cladograms representing the evolutionary history of sustainable manufacturing. However, after reviewing manufacturing cladistics a number of limitations are found and subsequent future research directions are identified. One major limitation of manufacturing classifications is that they are essentially a description of the past and only useful to companies that are struggling to compete, i.e. a benchmarking scheme to reach a certain level of performance. Although this would be useful in terms of sustainability in that certain sustainable structures and organisations could be identified and then strived for, the classification provides no assistance with some of the major problems associated with sustainable technologies and practices. One such problem occurs during implementation when uncertainty of outcomes arises. In addition, manufacturing cladistics says nothing about the future.

In attempt to overcome this obstacle, research is recommended to assess the potential synthesis of classifications with evolutionary systems modelling which has the capability of exploring future evolutionary trajectories. Evolutionary systems modelling is the subject of chapter 6. This new thinking, which has developed from the science of complex systems, concentrates on providing solutions to the problems of modelling evolutionary processes. The review of this literature concerns both common modelling assumptions and their associated models, and the main applications of this approach, particularly the evolution of ecosystems, as well as urban and economic systems.

After reviewing the literature and assessing its compatibility with manufacturing cladistics, which is a favourable assessment, the main research aim changed. The original aim was to develop cladograms of sustainable manufacturing. With the review of evolutionary systems modelling, it is contemplated that the research on the original aim is carried and then data collected for the evolutionary modelling so that simulations of future scenarios could be performed. However, this would constitute two large research projects, so it is decided that a pilot or feasibility study be conducted of the synthesis between manufacturing cladistics and evolutionary systems modelling. This is an extension to previous manufacturing cladistics research on automotive assembly plants. This specific classification is chosen as the practices and technologies are easily recognisable and pervasive in many manufacturing organisations. There are also several research papers that have been published.

A questionnaire study is devised, piloted and carried out. As this is an altogether new investigative approach, the methodology is of an exploratory nature rather than an established one and is described in chapter 7. The full methodological procedure describes the apparatus used, questionnaire design and piloting procedures, the target companies and their associated sector, a description of the evolutionary systems modelling program, the program's variables that may be manipulated, and the study's main aims and objectives.

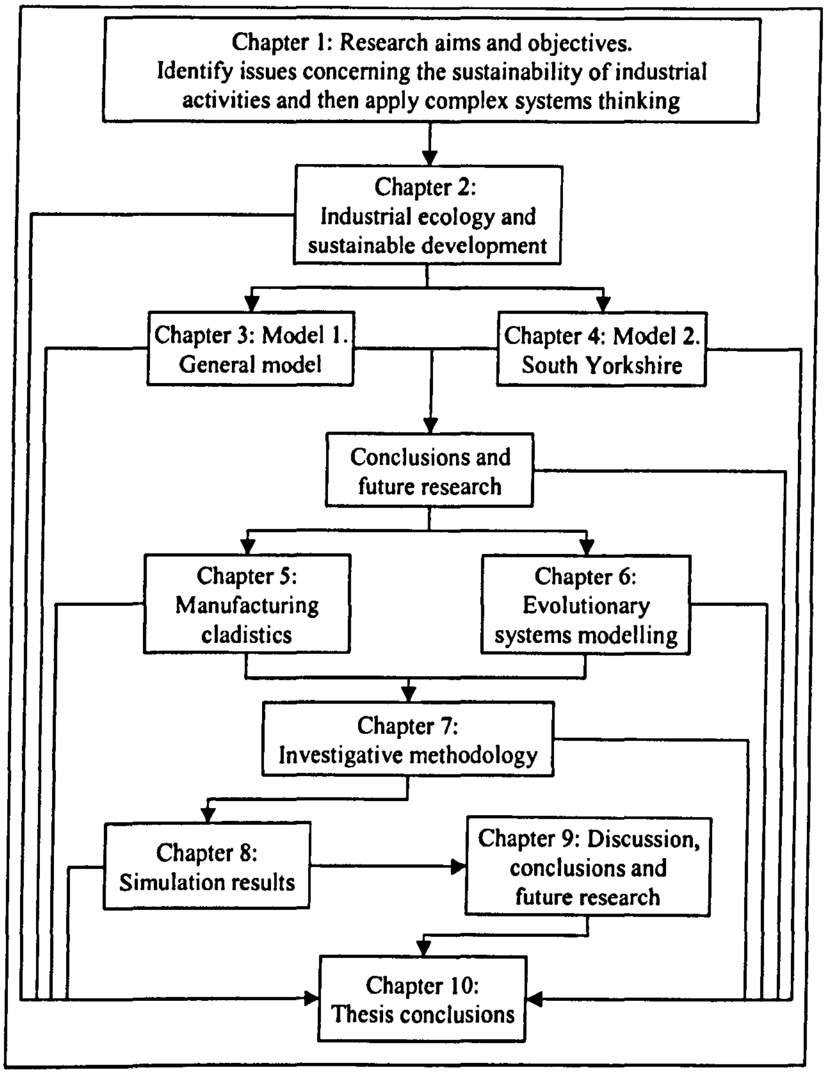
Chapter 8 presents the results of the research, specifically the exploration, through simulation, of the interactions between practices and technologies, which achieves the sixth research aim. There are five main sets of results. The first set explores organisational form and its evolution according to the original automotive assembly plant cladogram. This procedure involves evolving organisations from previous organisations in a consecutive manner. The second set of results provides an alternative perspective of the evolution by focusing on the performance of individual practices and technologies. The third set of results, offers another alternative perspective to the full evolutionary run (the first set of results) by launching organisations from new with all practices and technologies having an equal chance of survival. The fourth set of results explores the innovation process. With each evolutionary run, an organisation begins with one practice to which other practices and technologies are introduced randomly. The final set of results investigates organisational transformations and explores the consequences of adding new practices and technologies to existing organisations.

Chapter 9 discusses the significance of the results including the potential of the model to provide novel and unique insights into the evolutionary processes involved at this level of analysis. The model tested the internal harmony of organisations and potential conflicts between practices and technologies. These conflicts led in several instances to the failure of practices. The significance of this in terms of both practical implications and the cladograms previously developed are outlined. The main benefits of the evolutionary model was found to be through the insights provided into the outcomes of interactions between practices and technologies, the decision-making process, commitment issues, and risk, uncertainty and unpredictability in management. This demonstration of the usefulness of the new evolutionary framework for evolving industrial structure and exploring future scenarios for manufacturing satisfies the final research aim.

The chapter then speculates on the reasons why some of the practices and technologies failed during the simulations. Reasons offered include methodological flaws, misinterpretations, psychological barriers and flaws in the previous research. The chapter ends by outlining the originality and novelty of this investigation and recommends several areas of further research with methodological considerations, including evolving sustainable manufacturing organisations, modelling industrial ecosystems through the use of the evolutionary systems modelling, and an investigation into the bounded rationality of actors in the decision-making process.

The final chapter draws together the main conclusions reached throughout the thesis and the significance of the models at the two levels of analysis. The thesis structure is shown is figure 1.1.

Figure 1.1. Structure of the thesis



1.3. Originality

There are several aspects of this thesis that are novel and include:

- A model of the physical fundamentals of sustainable complex systems
- A model of industrial development that utilises thinking in non-equilibrium thermodynamics
- A synthesis of manufacturing cladistics and evolutionary systems modelling
- A unique data collection methodology to determine the interaction of common manufacturing technologies and practices
- The simulation of the evolution of manufacturing technologies and practices.

CHAPTER 2 – SUSTAINABILITY AND INDUSTRIAL ECOLOGY

2. Introduction

The actual concept of sustainable development was first officially debated at international level in 1987 with the contents published in *Our Common Future* by the World Commission on the Environment and Development (WCED, 1987). Building on this, it was again debated in 1992 at the *Earth Summit* in Rio de Janeiro by the United Nations Conference on Environment and Development culminating in *Agenda 21* (UNCED, 1992). This was in response to growing concerns of environmental and socio-economic problems that are now global in scale. Since then the literature relating to sustainable development, encompassing pure and applied, has expanded profusely (Pezzey, 1992). In fact, it has now become a concept familiar throughout many academic disciplines and governmental departments (Bruff & Wood, 1995). Industrial ecology has now emerged as the leading concept with which to represent and understand the transitions necessary for industry to become sustainable.

Although the notion of industrial ecology (IE) has been around for some time, being first proposed around the 1950s, it wasn't until the 1990s that academics and industrialists began to take it seriously as an organising concept with which to model the transitions necessary for manufacturing to become sustainable (Erkman, 1997). Since the seminal article of Frosch and Gallopoulos (1989) there has been much debate, many definitions and interpretations, numerous models ranging from the simple to the complex, various case studies of industrial ecosystems and symbioses, countless tools and, as with all new disciplines, several areas of ambiguities and inconsistencies, and as such many areas of further research and refinement.

To fully appreciate the concept and the work and research that have been conducted in IE, this chapter will first focus on sustainable development, particularly definitions, global and national problems, the strategies that have been developed and the progress that has been made. The focus of the chapter then turns to IE and starts by discussing the many definitions (and their implications) that have emerged. As there are now many IE models in the literature, these will be explored and evaluated in the next two sections. Typical models that have been proposed include the industrial metabolism models (Ayres, 1994; Newman, 1999) and the type I to type III industrial ecosystems (Richards, Allenby & Frosch, 1994; Graedel, 1996). These models are primarily concerned with recycling or 'roundput' issues. Other models have extended the ecological analogy to both diversity (e.g. Templet, 1999; Korhonen, 2001) and energy transitions (e.g. Templet, 1996; 1999; Buenstorf, 2000).

The chapter then highlights some of the many case studies that have emerged as well as their problems, including Kalundborg in Denmark, Styria in Austria, and the steel industrial ecosystem. Having reviewed all of the positives of this new discipline, the problems and issues are then explored, particularly:

- The ambiguity in definitions and the resulting wide-ranging (and in some instances, corrupt) interpretations
- Problems with some of the tools that are advocated
- Certain weaknesses in the overall construct of IE.

2.1. Sustainable Development: Definitions

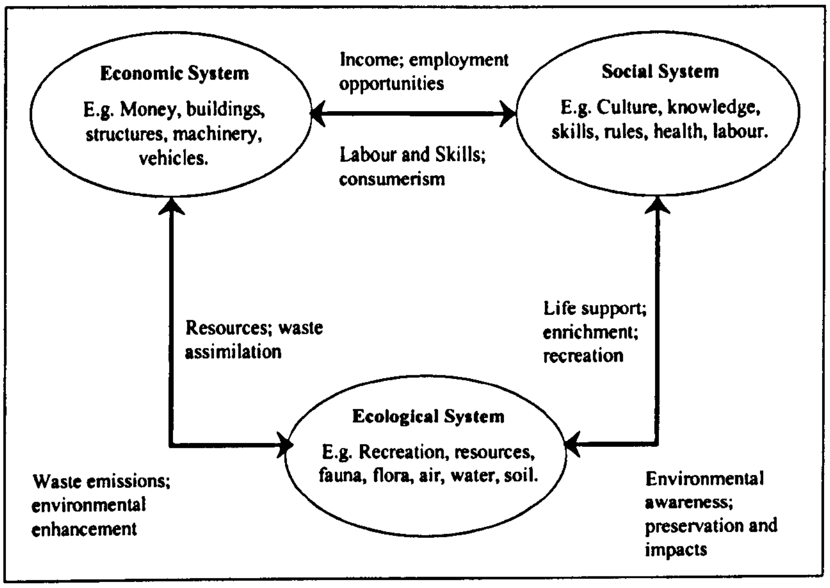
The most accepted definition of sustainable development (but see Beckerman, 1994), adopted by world-wide organisations, governmental, non-governmental, corporate and others, was proposed in *Our Common Future* (WCED, 1987). The Brundtland report, as it is known, argues that sustainable development is (WCED, 1987: 8):

> 'development which meets the needs of the present without compromising the ability of future generations to meet their own needs'.

Of particular importance in the translation from definition to strategy, emphasised in *Agenda 21* (UNCED, 1992), is the recognition that although all problems are global in scale, action and intervention can only be initiated locally. Different countries and regions face different problems either in nature or in scale. Nonetheless, there is now emerging consensus that most, if not all, countries are now interconnected and interdependent in the increasing globalisation of the socio-economic system, and thus must take responsibility for their own actions and effects that influence, both directly *and* indirectly, the global environmental and socio-economic problems (Welford & Gouldson, 1993; Welford, 1994; 1995; 1997).

Since the Brundtland report, many, more detailed definitions (see appendix 1) have emerged in the academic literature, more or less in line with this initial definition. Although in all definitions there is considerable emphasis on the environment, most explicitly recognise that it is human development (achieving at least the same or better living conditions and the widening of people's choices) respective of ecological, social and economic systems – the now consensual three 'pillars' or components of sustainable development (see figure 2.1).

Figure 2.1. Components and their interactions (adapted from DETR, 1999b)



2.2. Global Environmental and Socio-Economic Problems

There is now a consensus that the state of the global environment has been worsening for decades, with the most significant roots of decline starting with industrialisation (Elmer-Dewitt, 1989b). Although energy *usage* is not a problem, current means of energy *production* are. In 1989, eighty-eight percent of global energy relied on coal, oil and gas. Consumption exceeds natural production and deposition by one million times (Gibbons, Blair & Gwin, 1989). As such stocks are rapidly being depleted. However, other sources of energy, e.g. solar, wind-power and hydropower, are in line with nature and available with current technological capabilities (Elmer-Dewitt, 1989a; Odum, 1997b). The main consequence of fossil-fuel consumption is its role in the alteration of atmospheric chemistry. As can be seen from table 2.1, the change in composition is very slight. The main increases (and decreases) are in the trace gases that constitute less than 0.05% of the atmosphere. Although some fluctuation is caused by nature, e.g. volcano activity and natural periodic forest-fires, most alteration is through human activity, mainly fossil-fuel combustion, industrial- and agricultural-processes, biomass-burning, deforestation, landfills, and domestic appliances (Lemonick, 1989b; 1989a). The detrimental effects, however, are thought to be far reaching causing acid deposition, smog, depletion of the ozone layer, and global warming (Graedel & Crutzen, 1989). Acid deposition, the creation and deposition of nitric acid and sulphuric acid is more a regional, rather than global, phenomenon and associated with urban lifestyle.

Table 2.1. Trace gases: past, present and future (from Graedel & Crutzen, 1989)

Gas	Major sources	Total emissions per year (millions of tons)	Average residence time in atmosphere	Average concentration 100 years ago (PPB)*	Approximate current concentration (PPB)	Projected concentration in year 2030 (PPB)	Green-house effect	Strato-spheric ozone depletion
Carbon Monoxide (CO)	Fossil-fuel combustion, biomass burning	700/2000	Months	N. Hem. 40 to 80, S. Hem. (Clean atmospheres)	100 to 200, N. Hem. 40 to 80, S. Hem. (Clean atmospheres)	Probably increasing		
Carbon Dioxide (CO2)	Fossil-fuel combustion, deforestation	5500/~5500	100 years	290000	350000	400000 to 550000	+	+/-
Methane (CH4)	Rice fields, cattle, landfills, fossil-fuel production	300 to 400/550	10 years	900	1700	2200 to 2500	+	+/-
Nitrogen Oxide gases	Fossil-fuel combustion, biomass burning	20 to 30/30 to 50	Days	.001 to ? (Clean to industrial)	.001 to 50 (Clean to industrial)	.ool to 50 (Clean to industrial)		+/-
Nitrous Oxide (N2O)	Nitrogenous fertilisers, deforestation, biomass burning	6/25	170 years	285	310	330 to 350	+	+/-
Sulphur Dioxide (SO2)	Fossil-fuel combustion,	100 to 130/150 to 200	Days to weeks	.03 to ? (Clean to industrial)	.03 to 50 (Clean to industrial)	.03 to 50 (Clean to industrial)	-	
Chloro-Fluoro-Carbons	Aerosol sprays, refrigerants, foams	~1/1	60 to 100 years	0	About 3 (Chlorine atoms)	2.4 to 6 (Chlorine atoms)	+	+

*PPB: Parts per billion

Photochemical smog (i.e. ozone) is also accumulating at ground level (a reaction between nitrogen oxides, hydrocarbons, both of which are anthropogenic, and solar radiation) and is thought to be beginning to cause harm to both humans and nature

(Odum, 1997b). In contrast, ozone at the stratospheric level is being depleted, through human made CFCs, and also poses problems to both humans, e.g. cancer, and natural systems (DETR, 1999b). In addition, 'greenhouse gases', especially, carbon dioxide, along with methane, the CFC's, nitrogen oxides, and water vapour (Tietenberg, 1994), have increased by between 25-30% (Polunin, 1987; Lemonick, 1989b) since recordings began prior to industrialisation (Schneider, 1989). Carbon dioxide is thought to account for between 50-70% of the problem, CFC's for about 15%, and nitrogen oxides, water vapour and methane the rest; methane, per molecule, traps up to 20 times more heat than carbon dioxide (Lemonick, 1989b).

Carbon dioxide has been projected to double (to 600 parts per million) by 2050, if current anthropogenic practices do not significantly change (Lemonick, 1989b; Tietenberg, 1994). With this carbon loading of the atmosphere, the resulting surface temperature, based on results of global-circulation models, could increase by between 3 and 5.5 degrees Celsius (Schneider, 1989). The current average global temperature is thought to have already increased by 0.4% to 0.7% (DETR, 1999b). With the predicted rise in coastal sea levels and dramatically altered weather patterns, this could, obviously, seriously threaten major ecosystems, agricultural production and human settlements (Odum, 1997b).

General waste, from industry, construction and households, is arguably harmful to both the environment and human health (Langone, 1989). Much of the waste accumulating in landfills constitutes household waste, primarily packaging, much of which is unneeded and unwanted, and a lot of it recyclable. In 1989, Japan recycled about 50% of the countries general waste, Western Europe about 30%, and the US about 10%; the waste that has not gone to landfill or recycling centres, goes to the incinerators (Langone, 1989). However, this has major drawbacks. For example, a study in New Jersey found that the annual emissions from the daily incineration of 2000 tons of household waste included 5 tons of lead, 17 tons of mercury, 2000 tons of nitrous oxide, 700 tons of hydrogen chloride, 87 tons of sulphuric acid, 18 tons of fluorides and 100 tons of particulate matter (Hawken, 1993).

The main global social and economic problems are concerned with the rapid expansion of the world's population (UNFPA, 1991; PRB, 1999), the biophysical carrying capacity (Rees & Wackernagel, 1994), and the general social state of the world (Gladwin, Kennelly & Krause, 1995a). These socio-economic problems arguably exacerbate many of the environmental problems and vice versa (Myers, 1987).

Prior to industrialisation, the world's population stood at approximately 5-10 million. By 1950 the population numbered 2.5 billion, in 1987 it had doubled and in the year 2000 the six billionth person was born. Rates of population expansion, however, vary from region to region. Just over 1.18 billion people live in more developed countries and the annual natural increase is 0.1%, with a doubling time of 583 years. Developing countries are the home to 4.8 billion with an annual natural increase of 1.7% - a doubling time of 40 years (PRB, 1999). With current trends, it is predicted that developing countries will reach 'replacement level' fertility, i.e. no more growth, by around 2050, leaving the world with a population of around 12 billion people (Gladwin et al, 1995a).

The literature on the population phenomenon focuses on mainly two aspects that are highly interconnected. The first is the biophysical carrying capacity. A simple and elegant experiment conducted by Klein (1968) demonstrates the consequences of when a population exceeds its local carrying capacity. Klein introduced 29 reindeer to St. Matthew Island, an abundant resource base with no predators. It was calculated that the island could support between 1600-2300 reindeer. In less than twenty years the population exceeded 6000 and its carrying capacity - 3 years later the number was just 42 with only one male (which was infertile). Hardin's (1968) 'tragedy of the commons' is also relevant here (Potter, 1987; Tainter, 1988; Toufexis, 1989; Hern, 1990; Schwartzkopf, 1992; Zedler, 1993). Similarly, Vitousek et al (1986) calculated both the terrestrial net primary productivity of the world and then how much humans appropriated - it is now approaching 40%. It takes little imagination, with both this and the previous discussion on the state of the environment, to recognise the significant impact a doubling of the population, as projected, will have on both human development and the environment if current activities continue (Myers, 1987; Sancton, 1989a; 1989b; Diamond, 1991; Ludwig, Hilbron & Walters, 1993; Dasgutpa, 1995; Kearns, 1997).

2.3. National Environmental Problems

During 1999 the then UK government's Department of Environment, Transport and the Regions published two reports. These outlined both a strategy for future environmentally- and socially-responsible economic development, and 150 indicators with which to measure the scale of the problems and to monitor progress (unless otherwise noted, statistics are from DETR, 1999b). During the last three decades, the UK consumed annually between 200-230 million tonnes of oil equivalent (DETR, 1998a). Of the *existing* proven, probable and possible oil and gas reserves, approximately 6% were consumed during 1998 alone. Of the total energy consumption of the UK:

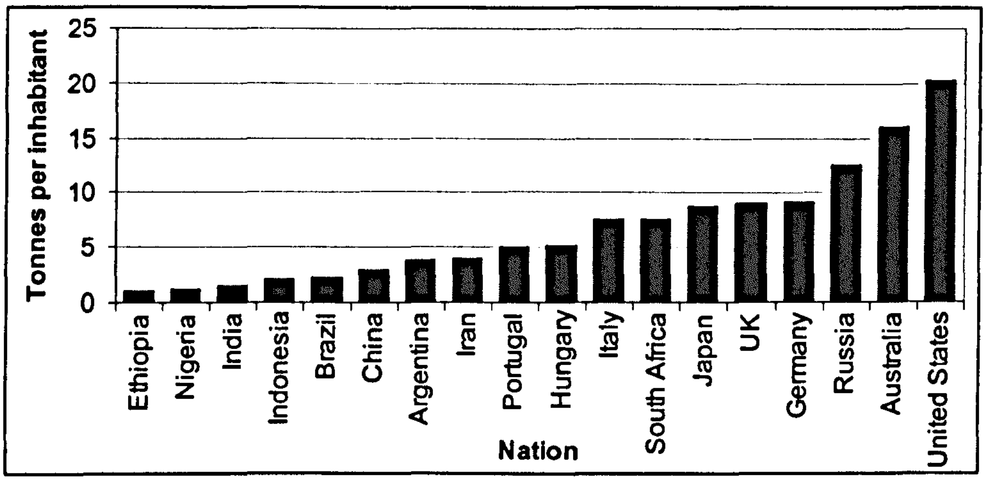
- Households account for 29%
- Industry accounts for 22%
- Road passengers account for 17%
- Services account for 13%
- Road freight accounts for 9%
- Other sources account for approximately 10%

During 1950 and 1998 gross domestic product (GDP) increased by over 200% while primary energy consumption increased by 60%. Thus the energy ratio (GDP/primary energy consumption) actually decreased by 50%. Prior to 1990 energy was primarily derived from coal and oil, which are rich in carbon emissions. During the 1990s however energy production shifted to gas and nuclear and an emphasis was put on renewable energy. Two-percent of electricity generation is from renewables:

- 54% is from large-scale hydropower
- 14% is from municipal solid waste combustion
- 13% is from landfill gas
- 9% is from onshore-wind
- 4% is from sewage sludge digestion
- 2% is from small-scale hydropower
- 3% are from other resources

In 1997, both developed and developing countries came to legally binding agreements (the Kyoto protocol) to reduce emissions of the main greenhouse gases. The UK is one of the main contributors to the carbon dioxide problem, but is on the decline. The United States is by far the worst (see fig. 2.2).

Figure 2.2. International emissions of carbon dioxide (from fossil-fuel combustion and cement manufacture) per head for selected countries: 1995 (from DETR, 1998b).



The majority of other UK pollutants that contribute to warming, acid deposition, smog, and human illness, are also on the decline. These include nitrogen dioxide, sulphur dioxide, carbon monoxide, particulates, and ozone. Agricultural pollutants (e.g. nitrogen, phosphorus, pesticides, dioxins and PCBs) are also in decline particularly with the rise of organic farming.

Anthropogenic waste is a huge problem for the UK. This includes solid waste from households, industry and commerce. Approximately 400 million tonnes of waste, of which approximately 20% is a derivative of industrial and commercial processes, is generated each year in the UK. Household waste (the majority indirectly generated by industry and commerce) is on the increase. To cope, the government has set a target for 30% recycling or composting by 2010.

Industrial recycling of metals has showed no trend during the last 15 years. Seventy percent of lead, 40% of aluminium, ferrous and copper, and 20% of zinc are recycled each year. Forty percent of paper and board, 20% of glass, and 3% of plastics are presently recycled annually. Five million tonnes of special or hazardous waste, i.e.

high environmental impact, was produced during 1997/8 and although there are annual fluctuations there appears to be no upward or downward trends.

It is estimated that industry spends over £4 billion (0.5% GDP) annually on environmental protection. Approximately 27% of this was spent on clean processes (specifically, 8% on actual clean processes and 19% on add-on equipment), 30% was spent on water quality protection, 20% on air quality and 20% on waste disposal, i.e. approximately 70% on clean-up. Between 1993 and 1997 the number of major water pollution incidents dropped from around 7000 to under 2000, 16% of the latter were prosecuted.

In recognising their environmental responsibility, just under 400 UK companies, over half of them manufacturing firms involved in electrical goods, machinery, chemicals and metals, voluntarily adopted either ISO 14001 Environmental Management System or the EU Eco-Management and Audit Scheme (EMAS), both internationally agreed standards. Of 77 of the FTSE 100 companies whom participated in a study conducted by Business in the Environment in 1998, 53 had internal environmental audit processes, 47 had organisational and performance environmental targets, 45 had publicly stated environmental objectives, 43 had involved stakeholders in environmental concerns, and 37 had jobs with descriptions with environmental responsibility. In all of these areas there was a 40% increase in participation from 1996. The government aims to have 75% participation rate of the FTSE 100 in a recognised environmental management system (EMS) by 2001. Of the next 250 top UK companies, 19% had adopted an EMS and a further 9% were working towards the adoption by 1999.

By 1999, approximately 21% (or nearly 8,600) of UK organisations with more than 50 employees were recognised as Investors in People - a National Standard. Only 2% (or nearly 4,500) of small organisations (10-49 employees) had this standard. A similar initiative, the Ethical Trading Initiative (ETI), has also recently been introduced and supported by the UK government. Ethical trading codes of conduct focus primarily on the people in the supply chain particularly in developing countries prone to exploitation. Organisations involved are mainly retail and wholesalers, non-governmental organisations and trade unions.

When comparing the UK to the US, France, Germany, and Canada, the labour productivity of the working population in both the manufacturing and service sectors, i.e. GDP per worker and hour worked, is on average 20% less. In 1970 total imports and exports totalled £75 billion each (1995 prices). In 1998, however, imports totalled approximately £265 billion and exports £245 billion. The negative trade balance has been present since 1986.

Imports can be associated with environmental and social exploitation in other countries, and is a key aspect in many sustainable strategies for industry and commerce. During 1994 business closures considerably exceeded business start-ups, when averaged across all sectors. The trend reversed during 1998 where start-ups exceeded closures. Some sectors, including mining, energy, water, manufacturing, agriculture, fishing, wholesale and retail, have persistently more closures than start-ups. Most of the net growth is in London and the South East and in the financial and business service sectors.

The UK social investment in relation to GDP (in such assets as health and social work, education, roads, transport, sewage, waste disposal and water) declined between the period 1973 and 1985 from approximately 2.75% to under 1.6%, at which point it increased again to 2.2% in 1992. In considering the 12 major regions of the UK there is considerable variation in GDP per head. Only London (by 40%) and the South East (by 7%) are above the UK average; N. Ireland (19% below), Wales (17% below), the North East (15% below), and then Yorkshire and the Humber (10.5% below) have the least GDP per head. Approximately 20% (or 65) local council authority areas have high to severe levels of deprivation, i.e. high unemployment, high crime levels, poor health, housing and education. These are mostly urban areas located in London, the North West and North East.

2.4. Progress and Strategies

During the 1990s there has been a series of calls for science and academia to begin tackling the diverse issues relating to sustainability (see, for example, Lubchenco et al, 1991; Ehrlich & Daily, 1993; Fuentes, 1993; Ludwig, 1993; Mangel, Hofman, Norse & Twiss, 1993; Mooney & Sala, 1993; Salwasser, 1993; Slobodkin, 1993; Socolow, 1993; Levin, 1998; Gibson, Ostrom & Ahn, 2000). Nonetheless, considerable progress has been made in both conceptual and applied domains. Numerous comprehensive strategies, models and tools have been developed for both the highly specific and the most general, for example:

- Manufacturing (e.g. Frosch & Gallopoulos, 1989; Costanza & Perrings, 1990; Gladwin, Krause & Kennelly, 1995b; Porter & van der Linde, 1995; Roberts, 1995)
- Energy use (e.g. Elmer-Dewitt, 1989a; Gibbons et al, 1989; Dincer, 2000)
- Resource use (Farzin, 1984; Meyer & Helfman, 1993; Pitelka & Pitelka, 1993; Policansky, 1993; Odum, 1997a)
- Agriculture (e.g. Crosson & Rosenberg, 1989; Costanza, 1993; Park & Seaton, 1996; Christensen et al, 1999; Dale et al, 1999)
- Waste disposal (e.g. Chiesa, Manzini & Noci, 1999; DETR, 1999c)
- Planning (Newman, 1999; Berke & Conroy, 2000)
- Green economies (e.g. MacNeill, 1989; Costanza, Wainger, Folke & Maler, 1993; Hawken, 1993; Azzone & Bertele, 1994; Cantlon & Koenig, 1999)
- For society in general (e.g. Brundtland, 1989; Clark, 1989; Ruckelshaus, 1989; Barbier & Markandya, 1990; Daly, 1990; Daly, 1994).

The discipline of industrial ecology has recently become the most popular organising concept with which to model and understand the transitions needed for the sustainability of industry. As researchers have argued that there are many parallels between natural and industrial systems and as natural systems have persisted for millions of years, the concept of industrial ecology has become very attractive. As the research in this thesis is concerned with both industrial regeneration and sustainability issues, industrial ecology is discussed in more detail next.

2.5. Industrial Ecology: Definitions

To get a better understanding of the notion of industrial ecology it is perhaps best to start with a look at the definitions that have been proposed. As yet there is no accepted standard definition that captures the ethos of IE and satisfies all researchers. However, there are many underlying themes common to most definitions. Frosch and Gallopoulos' (1989: 94) definition of IE is as follows:

> 'In such a system the consumption of energy and materials is optimised, waste generation is minimised and the effluents of one process . . . serve as the raw material for another process. The industrial ecosystem would function as an analogue of biological ecosystems.'

From this definition, Frosch and Gallopoulos hint that a *systems* perspective is required in the study of IE. They emphasise *energy* and *materials* as the focus and that both should be *optimised*. Frosch and Gallopoulos give an indication, without actually specifying, that a closed looping of materials is required, as waste is used as resources for another process. They also argue that the *biological analogy* is a useful way in which to understand industrial systems. Five years later, Allenby (1994: 47) argued that:

> 'Industrial ecology may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely – given continued economic, cultural and technological evolution.'

This definition, although similar, is more comprehensive and has an altogether different emphasis. Like the last definition, Allenby (1994) argues that a *systems perspective* is required to fully understand industrial ecosystems. However, he also stresses that it is a means to an end, which is *sustainable development*. In addition, they argue that the view taken of the industrial system is both of an *evolutionary nature* and that it needs to *integrate industrial activity with natural activity*. Evolution is seen as an important inclusion in the thinking. If optimisation was the only objective, the industrial structure would soon become rigid, uncompetitive and likely non-sustainable (Allenby, 1994). Lowe (1997) also stresses a systems perspective, the notion of sustainable development and the integration of industrial and natural systems. But as can be seen, optimisation is the overriding aim (Lowe, 1997: 74):

> 'Industrial ecology is a foundation for creating sustainable industry in a sustainable society. [IE is a] whole systems approach to design and management of the industrial system in the context of local ecosystems and the global biosphere.'

Frosch and Uenohara, in 1994, realigned their thinking and as can be seen is very similar to Allenby's (1994) definition (Frosch & Uenohara, 1994: 2):

> 'Industrial Ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimise resource use (and to minimize waste flows back to the environment), managers need a better understanding of the metabolism (use and transformation) of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms (markets, incentives, and regulatory structures) that encourage systems optimisation of materials and energy use.'

Although sustainable development is not specified per se, reducing environmental impacts as well as the optimisation of resource use, nonetheless, are the goals. They also introduce the idea of top-down pressure in the form of markets, incentives, and regulatory structures. Graedel, whose work has helped enormously to establish and extend the discipline, offered the following definition (1996: 70):

> 'Industrial ecology is the study of the means by which humanity can deliberately and rationally approach and maintain a desirable carrying capacity, given continued economic, cultural, and technological evolution. The concept requires that an industrial system be viewed not in isolation from its surrounding systems, but in concert with them. It is a systems view in which one seeks to optimise the total materials cycle from virgin

> material, to finished material, to component, to product, to obsolete product, and to ultimate disposal.'

This definition, like the others, emphasises the integration of industrial and natural systems, optimisation of resource use, and evolutionary processes, but goes further and includes the notion of carrying capacity and the cradle to grave perspective. Ehrenfeld (1997), with the above definitions in mind argues that IE has seven fundamental implications and are as follows:

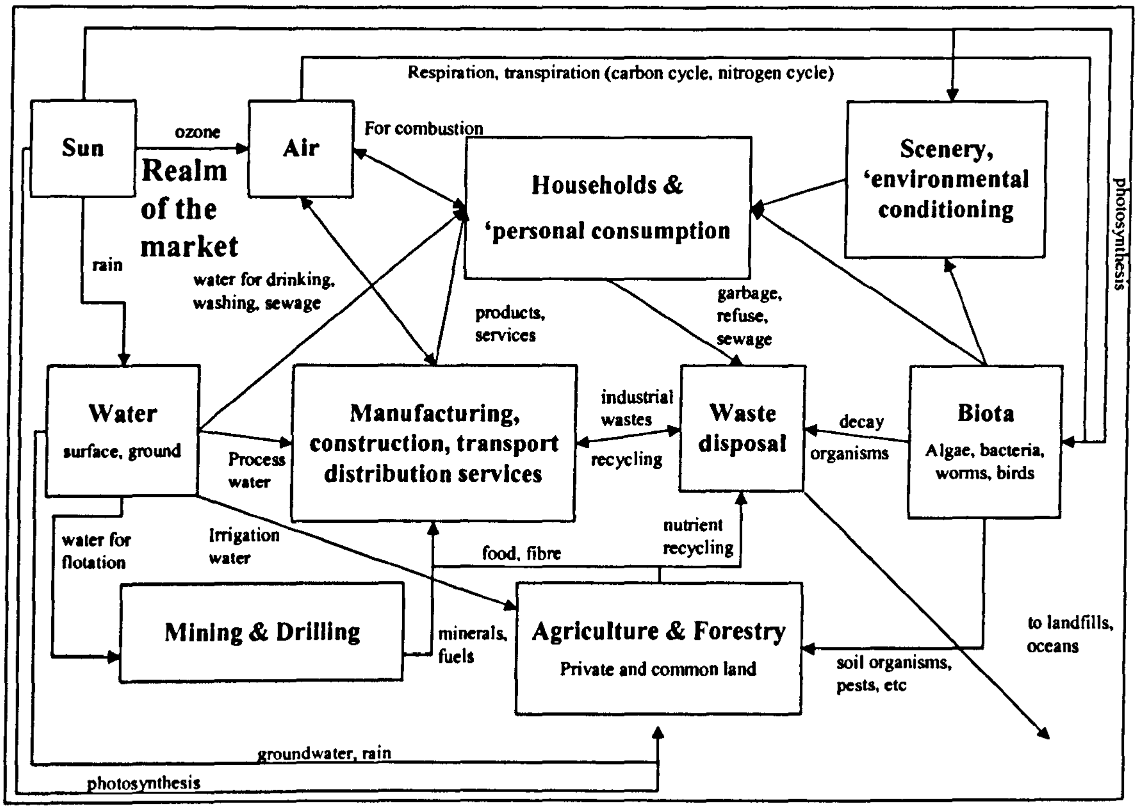
1. That metabolic pathways (the materials cycle) need to be improved
2. Materials closed-looping needs to be actively strived for
3. That the end product is increasingly dematerialised
4. Energy patterns are systemically organised and reduced
5. That industrial activity does not disconnect with, or overburden, natural systems
6. Policy adjustment to facilitate sustainable industrial evolution over suitable time periods
7. To put in place top-down structures and information flows to coordinate industrial activity.

With these definitions and implications in mind, models of industrial metabolism, firstly, and then industrial ecology will now be reviewed.

2.6. Industrial Metabolism

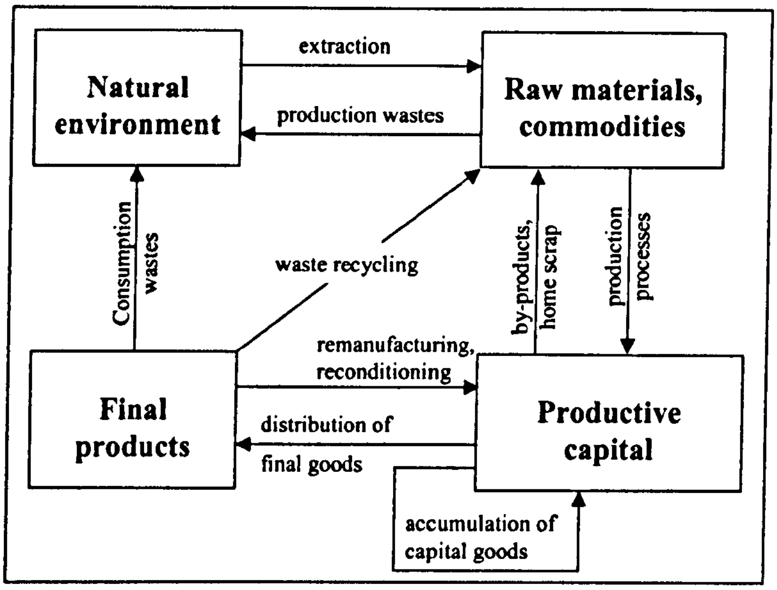
Ayres (1994) is perhaps the main proponent of industrial metabolism. He argues that there is a compelling analogy between the internal processes of biological organisms and industrial activities. This is seen most readily as biological organisms take in energy rich material, for growth, reproduction and/or to maintain its integrity, and then excretes the low-in-energy waste. Ayres goes on to argue that there are a number of levels that the analogy is applicable – global, national and regional economies (see figure 2.3). Furthermore he suggests that the most appropriate analogy is between the biological organism and the individual firm.

Figure 2.3. Industrial metabolism (from Ayres, 1994)



However, Ayres (1994) argues that the best use of the analogy is when the focus is on individual materials (see figure 2.4). If this metabolism view is taken, then when comparing natural 'closed' cycles, i.e. continually recycled, of materials (e.g. water, carbon, oxygen, nitrogen and sulphur), we see that industrial flows are generally open, and according to Ayres, unnatural and non-sustainable. If material flows are recorded and mapped holistically we are then able to rectify these problems. This view however, is very similar (if not the same) to many IE models. Indeed many researchers see the industrial metabolism perspective as just one component of IE.

Figure 2.4. Cycles of industrial materials (from Ayres, 1994)



Newman (1999: 220) has applied this approach in what he terms the 'extended metabolism model of the city'. Figure 2.5 sets out this model of human settlements. According to Newman, the metabolism approach enables the creation of a balance sheet of inputs and outputs so that wastes can be managed, energy requirements can be seen and resource decreases or increases can be elicited. Table 2.2 displays the results of a study on the material flows of Sidney, Australia.

Figure 2.5. The extended metabolism model of cities (from Newman, 1999)

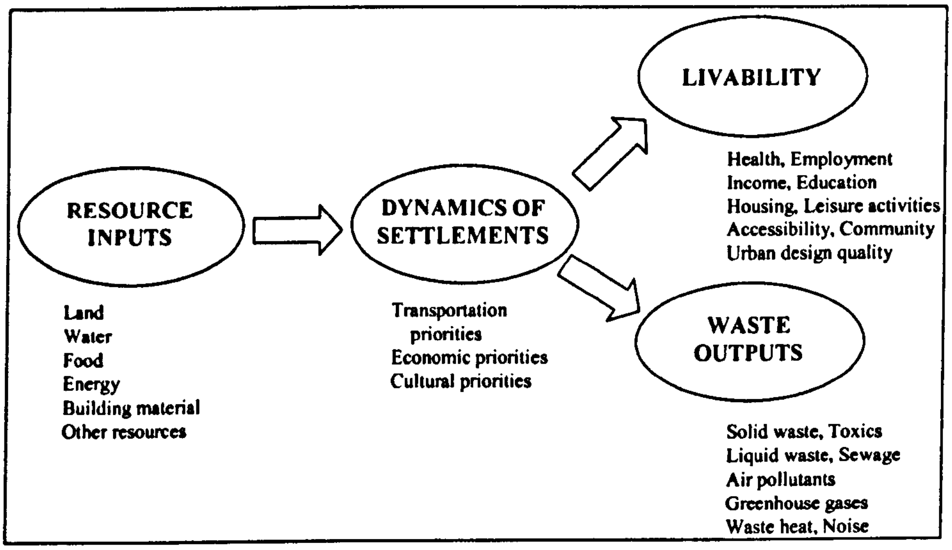


Table 2.2. Material flow trends in Sydney, Australia: 1970 and 1990 (from Newman, 1999)

	Population	
	Sydney 1970 2,790,000	Sydney 1990 3,656,500
Resources inputs		
Energy/capita	88,589 MJ/capita	114,236 MJ/capita
Domestic	10%	9%
Commercial	11%	6%
Industrial	44%	47%
Transport	35%	38%
Food/capita	0.23 tonnes/capita	0.22 tonnes/capita
Water/capita	144 tonnes/capita	180 tonnes/capita
Domestic	36%	44%
Commercial	5%	9%
Industrial	20%	13%
Agriculture/Gardens	24%	16%
Miscellaneous	15%	18%
Waste outputs		
Solid waste/capita	0.59 tonnes/capita	0.77 tonnes/capita
Sewage/capita	108 tonnes/capita	128 tonnes/capita
Hazardous waste		0.04 tonnes/capita
Air waste/capita	7.6 tonnes/capita	9.3 tonnes/capita
CO_2	7.1 tonnes/capita	9.1 tonnes/capita
CO	204.9 kg/capita	177.8 kg/capita
SO_x	20.5 kg/capita	4.5 kg/capita
NO_x	19.8 kg/capita	18.1 kg/capita
HC_x	63.1 kg/capita	42.3 kg/capita
Particulates	30.6 kg/capita	4.7 kg/capita
Total waste ouput	324 million tonnes	505 million tonnes

Accounting in this way can help set indicators and targets for future development. Newman (1999) argues that there are five predominant areas for concern:

1. Energy and air quality (e.g. reduce energy usage, increase energy efficiency and renewable energy sources, and reduce air pollutants)
2. Water, materials and waste (e.g. reduce water use, increase industrial recycling and increase organic waste flows to soil amendment uses)
3. Land, green spaces and biodiversity (e.g. increase green space, preserve greenfield sites and encourage city wildlife)
4. Transportation (e.g. reduce car use, decrease parking spaces and encourage cycling)
5. Liveability, human amenity and health (e.g. reduce infant mortality, increase educational attainments and reduce crime rates).

Newman (1999) also argues that the extended metabolism model can be applied at a range of levels and human activities. For example, industrial areas (the typical focus) can take a holistic view of total use of resources as well as the subsequent wastes.

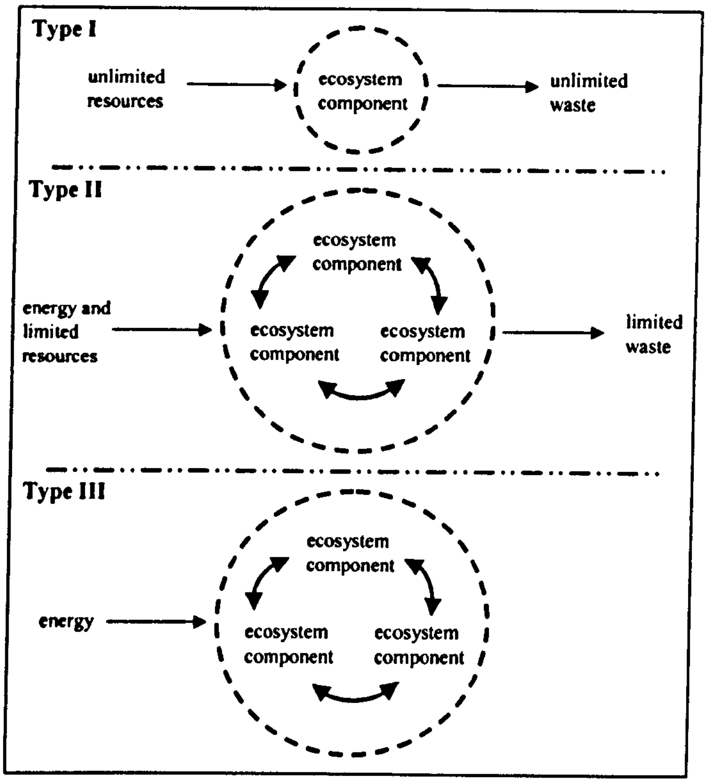
Mutual solutions could then be found between existing practices to help reduce resource use and minimise environmental impacts. Individual companies could also utilise the approach and create sustainability business plans. Households as well as their neighbourhoods can also monitor the flow of materials and lessen environmental impacts and increase the quality of life. Urban projects could also be assessed in terms of sustainability indicators. There are at least two instances of this in practice (e.g. Diver, Newman & Kenworthy, 1996; Arief, 1998). Comparisons can also be made between cities and regions and benchmarking schemes could be introduced.

As can be seen form Newman's (1999) study, the industrial metabolism model can be very useful for tracking material and energy flows and subsequently identifying improvements and/or related activities where symbioses can be developed. However, the concept is perhaps better utilised in conjunction with the IE perspective, which along with the industrial metabolism technique, takes a more comprehensive view of the industrial system.

2.7. Industrial Ecology

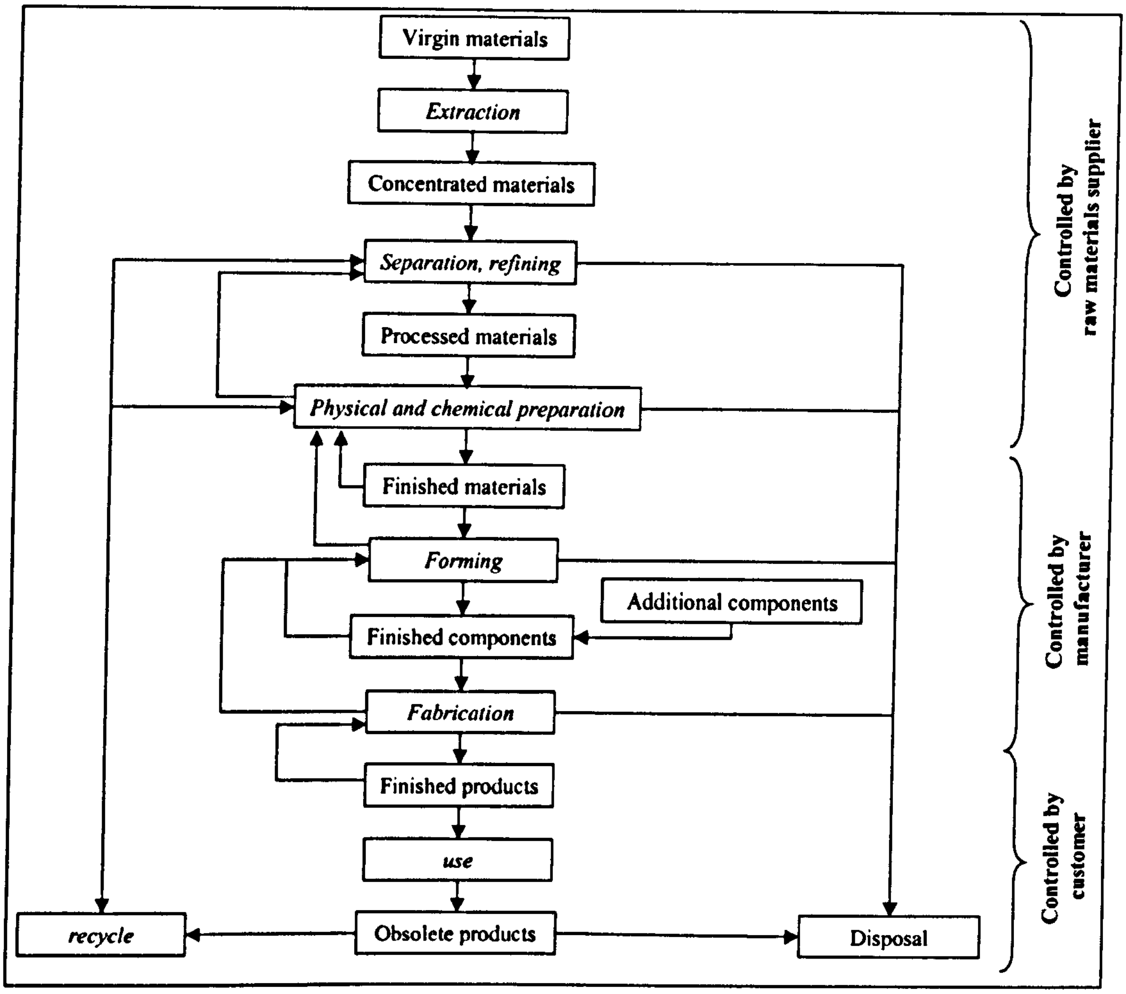
IE intends to be a representation of the total of human activity (Richards et al, 1994; Graedel, 1996; Commoner, 1997; Pizzocaro, 1998). This means that, for example, mining, manufacturing, agriculture, construction, energy production and use, transportation, and product consumption and disposal, should be viewed in whole. The perspective is not limited to within the single factory or the life cycle and environmental impacts of one product (much like industrial metabolism), but the whole ensemble of activity. As with industrial metabolism, concepts and models of natural systems, particularly ecosystems, are utilised. Graedel (1996), for example, finds it useful to look at the usual (or ideological) view of ecosystem development. A very simplistic view of this is the Type I to Type III systems (see figure 2.6).

Figure 2.6. Material flows in Type I – III ecosystems (from Graedel, 1996)



Type I ecosystems typically represent very immature systems, when space and resources are plentiful. Material flows are almost always linear – they enter the system, energy and nutrients are extracted, and the degraded materials leave as unutilised waste. However, as the system grows and as both space and resources become scarcer, a degree of material recycling occurs as decomposer populations begin to grow limiting the flow and impact of waste materials. This is a Type II ecosystem. Type III ecosystems represent fully mature ecosystems where most of the available resources are actually contained in the ecosystem– actual virgin resources have been extracted and are virtually non-existent. This system has achieved complete cyclicity. When this view is mapped onto industrial activities, Graedel (1996) argues that most are at the Type I stage with a minority achieving some resemblance of Type II. No industrial system has yet achieved Type III. A typical industrial ecology model of the whole process can be seen in figure 2.7. There are essentially three groups of people in control of the materials flow – the virgin material suppliers, the manufacturers, and the consumers. As can be seen there are four main waste flows. This observation, as Graedel (1996) is only possible when an IE model, such as depicted in figure 2.7, is developed (Ayres, 1994; Erkman, 1997; Frosch et al, 1997).

Figure 2.7. An IE model of the materials life cycle (from Graedel, 1996)



However, there are a number of points to make of this type of modelling. One important point (that most IE researchers and practitioners fail to mention) is that complete cyclicity in nature is only achieved when virgin resources are completely stripped from the environment (a point that will be returned to in chapter 4). Another point, is that this view of IE is not that far different from the concept of industrial metabolism. However, there are different views and approaches within IE as Boons and Baas (1997) point out in their typology of the different forms of IE. They argue that there are essentially five different types that differ in their scope:

1. The product life cycle perspective
2. The material life cycle perspective
3. The geographical perspective
4. The sectoral perspective
5. The perspectives that ignore boundaries.

These perspectives, however, have certain implications for the organisations under study (see table 2.3).

Table 2.3. IE perspectives and organisational implications (from Boons & Baas, 1997)

Industrial ecology types	**Organisational implications**
Sector	Organisations for coordination are available Competitive dependency precludes extenisve cooperation Limited interrelatedness as aimed for in industrial ecology
Product/material, life cycle	Intermingling of competitive and symbiotic dependency: fewer barriers to cooperation Coordinative institutions are not available Cognitive/institutionally complex to determine the right actions
Geographical area	Dependency is not automatically present, and must then be based solely on industrial ecology Authoritative coordination institutions are available (regional governments and/or industrial organisations) Separation consumption/production Top-down or interdependent approach
Miscellaneous	Bottom-up appraoch Local optimisation No rationale Dependency is not automatically present, and must then be based solely on industrial ecology

The product life cycle perspective draws a boundary around the economic actors – the producers and consumers. This perspective concentrates on the environmental impacts of the product at each defining stage of the products life cycle, from virgin material extraction to final disposal (and ideally re-use or recycle). This approach has perhaps been the most attractive and adopted by many practitioners, consultants and even governments (e.g. DETR, 1999b). The material life cycle approach takes a similar perspective to the product approach, but concentrates on individual materials with the boundary drawn around the economic actors handling the material. This is another popular approach, with examples including steel (Szekely, 1996; Sagar & Frosch, 1997), copper (Ayres, 1994), paper (Ekvall, 1999), municipal waste (Bjorklund, Dalemo & Sonesson, 1999), textiles (Schwarz & Steininger, 1997; Muezzinoglu, 1998) and plastics (Verschoor & Reijnders, 1999). The geographical perspective, utilising natural or political boundaries, is also a common level of analysis with examples including Kalundborg, Denmark (e.g. Lowe, 1997), Styria, Austria (Schwarz & Steininger, 1997), and Massachusetts, USA (Sagar & Frosch, 1997). The sectoral perspective draws the boundary around actors involved in similar industrial activities. This is a more difficult approach but is the level of analysis most appropriate for environmental benchmarking schemes. There are also IE studies that ignore boundaries and concentrate on any symbioses without respect for materials, activities, geography or sector. The aim is to find inputs for outputs, that is, to link companies in terms of the utilisation of wastes as resources.

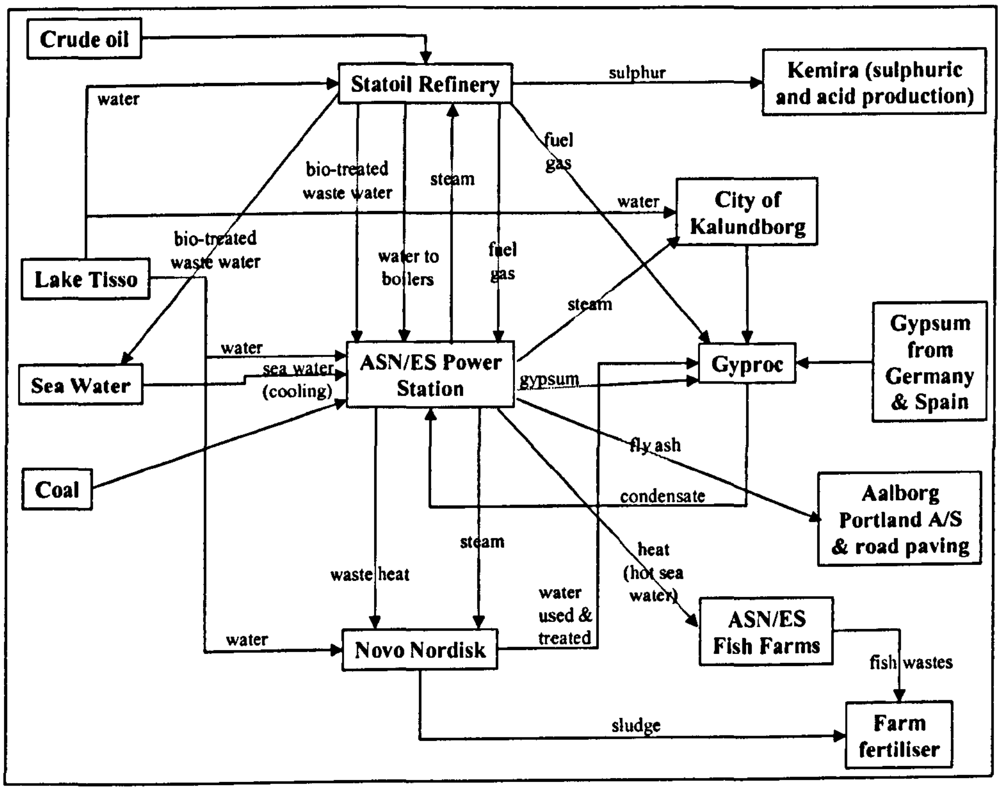
Korhonen (2001) takes the IE perspective even further by not only focusing on recycling (or to use Korhonen's term '*roundput*'), but also *diversity*, *locality* and *gradual change* – the 'four ecosystem principles for an industrial ecosystem'. Korhonen (2001) argues that the survival of the ecosystem is critically dependent on diversity (see also Templet, 1996; 1999). This diversity needs to be present at several levels of organisation – in organisms, in populations of species, and at the level of the ecosystem. There also needs to be diversity in interdependencies, in relationships (e.g. co-operative structures, symbioses and mutualisms), and in information flows. Diversity creates strong flexibility and adaptability, and is essential for coping with changes in the environment. In terms of industry, Korhonen (2001) sees the optimisation principle of the old Fordist or Taylorist regimes, which leads to widespread homogeneity, as one of the main barriers to diversification and long-term survival or sustainability. However, it is also recognised that the industrial community is beginning to realise the importance of quality, cooperation, and of different production systems to combat fluctuations in market demands.

Korhonen (2001) argues that industrial systems should also adhere to the locality principle. In practice regional economies must replace imported resources with local resources and renewables (for energy) and accept and adapt to the local limiting factors. This in turn would reduce transportation and increase the regional co-operative structures. However, one criticism of this principle is that Korhonen (2001) fails to recognise the severely restricting economic implications of this principle. Furthermore, it must also be recognised that in natural systems, this is not an overriding principle. For example, although some materials and nutrients are of a localised nature, many are not. For example, the hydrological, carbon and nitrogen cycles as well as certain minerals are global in scale (Lovelock, 1989a; Krumbein & Schellnhuber, 1992; Lovelock, 1997). Gradual change is also an important factor in Korhonen's (2001) view of a perfect industrial system. Industrial evolution must take account of non-renewable resources and must not be tempted by the rapid effects of cultural evolution in as much as the rapid cycles of fads and fashions. When implementing environmental management systems, the gradual change principle most readily applies to both the change of material flows from non-renewable to renewable resources and through increasingly trying to exploit waste flows. It also applies to the other two principles – diversification and localisation.

2.8. Case Studies

The most commonly cited example of an eco-industrial park, indeed the first industrial symbiosis to be officially recognised in academia (in 1989), is the Kalundborg Industrial Symbiosis on the Danish island of Seeland (see figure 2.8). The most important companies were and still are the largest and include an oil refinery, plasterboard plant, coal-fired power plant and a pharmaceutical plant. What is interesting about Kalundborg, like several other cited examples, is that it developed spontaneously without any external pressure (Lowe, 1997).

Figure 2.8. The industrial symbiosis at Kalundborg



The impetus to develop these recycling structures was purely economic – both to reduce the costs increasingly associated with waste disposal and as an extra income-producing service for other companies located nearby. The Kalundborg complex revolves around five large, core companies (Desrochers, 2002):

1. Asnæs Power Station which is Denmark's largest coal-fired, power station with 1,500 megawatts capacity
2. Statoil Refinery which is again Denmark's largest with a capacity of up to 4.8 million tons/year
3. Gyproc, annually producing 14 million square metres of gypsum plasterboard
4. Novo Nordisk, a large biotechnological company, with an annual turnover of $2 billion, producing both pharmaceuticals and industrial enzymes
5. The city of Kalundborg, with 20,000 residents supplied with both heating, through the district heating system, and water to homes as well as industries.

The symbioses first started when Gyproc moved to Kalundborg approximately 30 years ago, to take advantage of the fuel gas, a waste stream from Statoil. Since then numerous bilateral exchange agreements have been made to take advantage of both energy and material flows. In addition to the Gyproc and Statoil agreement, in 1981, the Asnæs Power Station agreed to supply the city of Kalundborg with steam for its district heating system and thereafter signed up Statoil and Novo Nordisk. With the new district heating system, 3,500 oil furnaces were decommissioned which significantly reduced non-point air pollution. The power station also switched sources of water, from lake Tisso to seawater, reducing the consumption of fresh water. It was then agreed that some of the waste stream, which is uncontaminated as it is used for cooling purposes, was to be re-directed to a nearby fish farm to replenish 57 ponds. In 1992, another significant agreement was made between the Asnæs Power Station and Statoil. To reduce the consumption of coal, Statoil, after installing a sulphur recovery unit, began supplying the power plant with surplus, and now 'clean', refinery gas.

The materials recycling began in 1976 when Novo Nordisk began supplying sludge from their processes to a nearby farm for fertilisation purposes. Shortly after, the fish farm also began supplying their sludge from their water treatment plant. The supply from both of these sources represents a large part of the material exchange network with over 1 million tons supplied per year. The cement factory began to buy the desulphurised fly ash from the Asnæs Power Station. The power plant also produces calcium sulphate (gypsum) when it reacts the SO_2 with calcium carbonate in its stacks, which constitutes two-thirds of Gyproc's demand. Statoil's sulphur recovery unit produces pure liquid sulphur, which is supplied to Kemira whom produces sulphuric acid. Finally, Novo Nordisk's insulin production processes results in excess yeast, which is supplied to local farms to feed their pig livestock.

In terms of gains with sustainable development in mind, the symbiosis complex has invested $60 million in its infrastructure, which has returned $120 million in revenues and cost-savings. The recovery, re-use and recycling activities have reduced pollution in several media including air, water and ground pollution. It has also helped the conservation of water and other resources.

Desrochers (2002), in trying to elicit why the Kalunborg system is successful in both economic and environmental domains, summarises some of the views of those involved in the network:

- Contractual agreements are always negotiated on a bilateral basis
- That agreements must be economically attractive
- That companies do not take up opportunities outside their core activities
- That risks are minimised
- That the evaluation process is only considered from within each company (a systemic evaluation is not taken).

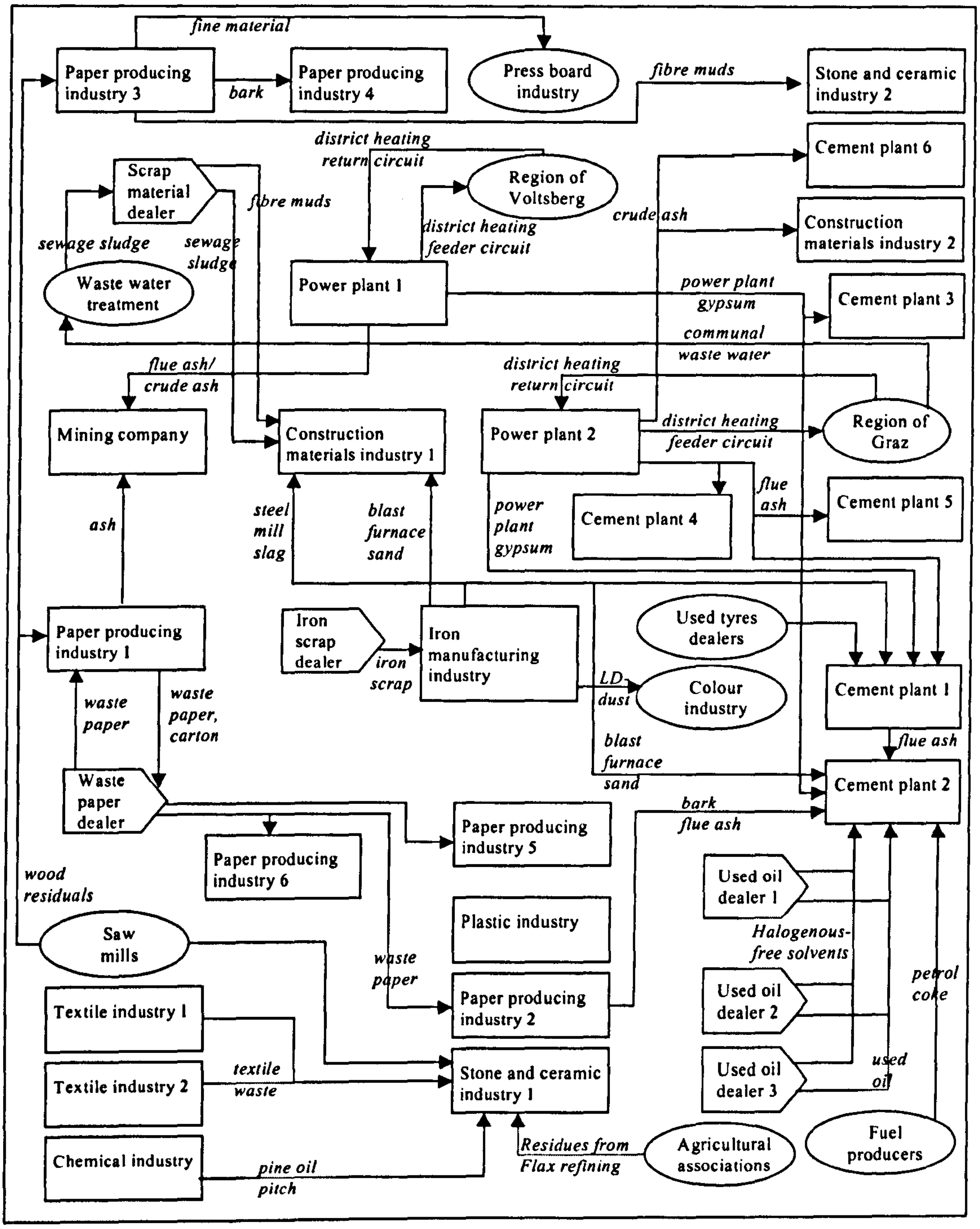
Furthermore, its helps if:

- The industries with the agreements are both different, in terms of activities, yet compatible, in terms of material flows
- That agreements are voluntary
- That regulatory agencies are fully involved
- That both companies are located near each other
- That positive human relations are fostered (the managers all know each other).

Although this example of an industrial symbiosis offers many other industrial complexes a guiding principle in that it is both economically viable and has reduced its environmental impact, in terms of sustainable industrial development it is nonetheless without criticism. One criticism is that although the network's means of production is evolving in line with the ethos of sustainability, its actual products in many instances are arguably far from sustainable. This is most notable with both Statoil, an oil refinery, and the Asnæs Power Station, whose main source of energy production is coal. Both coal and oil are considered to be non-renewable resources and contribute significantly to several areas of environmental concern such as global warming, climate change, and human illness. A second criticism is that the network, being connected in the majority of cases by physical, hard-pipe connections, is highly rigid and may be vulnerable to certain external pressures. Changing technologies, both small-scale, such as a production process, or large-scale, such as those requiring different supplies (e.g. sustainable pine yield or even wind power instead of coal) could have dramatic effects on the whole system, perhaps resulting in collapse. A second problem would occur, for example, if the Asnæs Power Station was taken by another power company, and didn't want such agreements in place. Although unlikely these issues raise questions about the network's future prospects.

The second case study to be reviewed was inspired by the research on Kalundborg. Schwarz and Steininger (1997), in a study that set out to determine whether there were any other recycling and symbiotic structures elsewhere, found another similar, but far more complicated, industrial ecosystem located in Styria, Austria, which again emerged spontaneously. They began their analysis with a large basic goods company, traced the waste streams of this company and other associate companies, as well as forms of recycling cooperation, until a geographic boundary was reached (see figure 2.9). One important omission, however, was that data from the material flows between the industrial and surrounding natural system were not collected. Participating industries in the network include companies focused around textiles, paper production, stone and ceramics, cement, construction materials, power generation, mining, metal scrap, plastics, tyres, iron manufacturing and agriculture. All companies offered waste material and most companies accepted certain types of waste. What is interesting in a number of cases is that the waste material from some companies was of a higher quality than the previous virgin material.

Figure 2.9. Recycling structures in Styria (from Schwarz & Steininger, 1997)



As with Kalundborg, the relationships and symbioses that developed were due to economic factors. Additional revenue could be gained, as accepting waste could be charged as a service. The recycling network also helped avoid the costs and taxes now associated with waste disposal. Schwarz and Steininger (1997) argue that certain circumstances are needed to trigger off the spontaneous development of recycling symbioses:

1. That the price difference between virgin and waste material (including transportation and processing) are significantly different
2. That the quality of the material is easily determined and is constant
3. That there is a certain amount of redundancy of companies that have the appropriate technology for waste consumption
4. That there is constant and significant pressure from markets dealing with both virgin material and waste disposal
5. That frankness and trust is developed and nurtured between companies (many failures are attributed to a breakdown in human relations).

On top of the economic advantages of the Styrian system are the environmental benefits with reduced waste, reduced virgin material requirements, reduced emissions and an extension to the lifetimes' of landfills (see table 2.4). A total of 1,497,445 tonnes of waste are treated in the system, which represents 'a substantial part of the total regional waste flows' (Schwarz & Steininger, 1997: 50).

Table 2.4. Styria: Waste treatment and recycling amounts (Schwarz & Steininger, 1997)

Waste category	*Amount (t)/year*
Used oil	11,366
Waste paper/carton	437,000
Used tires	7,600
Halogen-free solvents	305
Blast furnace sand	111,700
Ash, bark flue ash	159,037
Pine oil pitch	3,740
Crude ash	11,700
Petrol coke	2,570
Power plant gypsum	9,352
Textile waste	304
Wood residuals	447,200
Residues of flax refining	571
Sewage sludge	15,000
Iron scrap	90,000
Steel mill slag	180,000
Total	**1,497,445**

One important conclusion from Schwarz and Steininger's (1997) study was that there maybe many such recycling and symbiotic structures that exist but as yet not recognised as such. Indeed, Cote and Cohen-Rosenthal (1998) have identified several such sites in the US (table 2.5) and other potential sites in Canada (table 2.6).

Table 2.5. Eco-industrial parks identified in the US (Cote & Cohen-Rosenthal, 1998)

Site	Characteristics
Port of Cape Charles, Virginia	Sustainable technologies, natural coast features
Fairfield, Baltimore, Maryland	Transformation of an existing industrial area, co-generation, waste re-use, environmental technology
Brownsville, Texas	Regional or virtual approach to waste materials exchange, marketing
Riverside, Burlington, Vermount	Agricultural industrial park in urban setting, bio-energy, waste treatment
Chattanooga, Tennessee	Redevelopment of inner city and former military manufacturing facilities, green areas, environmental technology
Green Institute, Minneapolis, Minnesota	Inner city, small scale green business incubator, waste material re-use
Plattsburgh, New York	Redevelopment of a large military base, resource and waste management, EMS
East Shore, Oakland, California	Resource recovery-based park, landscaping, energy efficiency
Londonberry, New Hampshire	Small scale, community-based park
Trenton, New Jersey	Redevelopment of an existing industrial area, clean industries
Civano, Tucson, Arizona	A new development integrating commercial and residential, environmental businesses, natural features
Franklin, Youngsville, North Carolina	A commercial complex with renewable energy and environmental technologies
Raymond, Washington	A new park within a second growth forest, recycling of solid and liquid wastes
Skagit County, Washington	A new park with support systems and centres, environmental industries
Shady Side, Maryland	Renovation of existing facility, maintaining jobs, small scale environmental and technological businesses

Table 2.6. Potential eco-industrial parks in Canada (Cote & Cohen-Rosenthal, 1998)

Province	Key Industries
Vancouver, British Columbia	Steam generator, paper mills, packaging, industrial park
Fort Saskatchewan, Sask.	Chemicals, power generation, styrene, PVC, Biofuels
Sault Ste.Marie, Ontario	Power generation, steel, paper mill, flakeboard mill, industrial park
Nanticoke, Ontario	Thermal generating station, oil refinery, steel mill, cement, industrial park
Cornwall, Ontario	Power and steam generation, paper mill, chemical, food, electrical equipment, plastics and concrete products
Becancour, Quebec	Co-generation plant, chemical plants (H_2O_2, HCL, Cl, NaOH, Alkylbenzene), magnesium, aluminium
Montreal East, Quebec	Co-generation plant, petrochemicals, refineries, compressed air, gypsum board, metal refinery, asphalt
Saint John, New Brunswick	Power plant, paper mill, oil refinery, brewery, sugar refinery industrial parks
Point Tupper, Nova Scotia	Generating station, pulp and paper, building board, oil refinery

However, the Styrian system shares the same problem with the Kalundborg system, in that although the means of production is developing in-line with sustainability principles, many of the resources used and the end products are again, arguably, far from sustainable (e.g. power plants, plastics, tyres and oil dealers). However, on a more positive note and unlike the Kalundborg system, this network is not characterised by physical connections, which reduces the rigidity of the system. In addition, there is also plenty of redundancy (i.e. several paper producers, power plants, cement producers, oil dealers and textile producers) creating flexibility and improved adaptation capabilities, which, in turn, increases the likelihood of survival in changing and volatile environments (Wallner, 1999).

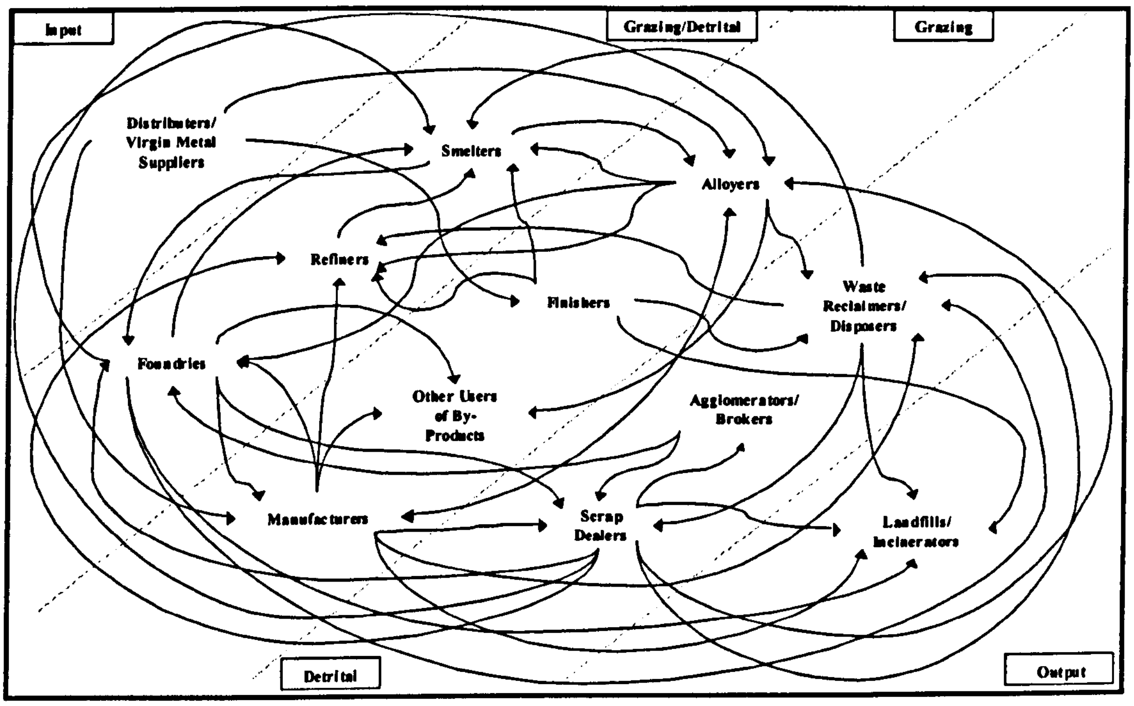
One last case study to highlight is the metals-manufacturing industry studied by Frosch, Sagar and colleagues (e.g. Frosch & Gallopoulos, 1989; Frosch et al, 1997;

Sagar & Frosch, 1997). Although an important study in its own right it also provided the inspiration for the models developed in chapters 3 and 4 (see also Szekely & Trapaga, 1995; Szekely, 1996). It also differs somewhat from the other two case studies as the focus, although geographical, was more restricted to copper/copper alloys and lead. The aim of the research was to determine:

- What an industrial ecology looks like
- What geographical features there are
- How material flows work within and between companies
- How material flows are internally and externally manipulated
- How the system could reduce impacts on the environment.

The metals-manufacturing industry was the subject of study as metals represent a substantial fraction of industrial consumption, are unlikely to be substituted in the near future, and are involved in one of the oldest industrial systems. The companies were involved in manufacturing, fabrication, finishing, recycling and disposal, and secondary processing. Tracking the materials flows from these firms led to the diagram shown in figure 2.10.

Figure 2.10. Metals manufacturing system (adapted from Sagar & Frosch, 1997)



This systems-level analysis enabled a number of insightful observations to be made. Sagar and Frosch (1997) found that the flow of materials within the individual companies demonstrated an array of complexities dependent on the different types of operations within each company – the more processing operations, the more complex the flow of materials. The flow within the system as a whole was also complex with each firm connected in often very unique relationships making it difficult to develop generalisations. One interesting observation was that there was very little leakage of materials from the system, with only 0.5% copper leakage and 4.5% lead leakage (much of this lead leakage due to one firm). The key to the recycling process was largely down to certain sectors, particularly scrap dealers and the secondary processors such as smelters and refiners. Sagar and Frosch (1997) also found several companies that although occupied small niches (e.g. waste agglomerators/brokers) were very significant in the facilitation of material flows around the whole system.

Another important observation is that although metal was the focal material, other materials, such as sand, plastics and water, were also involved and that the metals system was only a subsystem of a wider industrial ecosystem. Evolution also played a significant role as the system is continually changing as some species become extinct and other species and their relationships and connections evolve. Sagar and Frosch (1997), when comparing this system with the Kalundborg system (the rigidity of the hard-pipe connections and long-term agreements), argue that there appears to be far more adaptive responsiveness, flexibility and dynamism which will benefit the system in terms of adapting to changing external stimuli. This adaptive responsiveness, they argue, is the result of diffuseness over a large geographical area.

The information flows between the companies, generally disregarded in most other examples, was argued to be as important as the flow of materials. Species facilitating information flows were identified as technical and regulatory consultants and equipment and service vendors. Government (both state and federal) agencies were generally not involved in the flow of information. Furthermore, although agreeing in principle, all firms however displayed frustration with regulation agencies and reported, in many instances, adversarial relationships. A final important observation, which was also identified in the last two case studies, was that the main driving force behind the closed-looping phenomenon is purely economics. In their words they found (Sagar & Frosch, 1997: 44):

> 'that the factors underlying decisions taken by firms regarding metal flows are predominated by economics (to stay in business and maximise profits), regulatory concerns (to allow them to continue operations), and liability considerations (to prevent future economic costs).'

It is worth noting that the regulatory concerns and liability considerations that they emphasise are arguably fundamentally economic in origin.

To conclude this section, a number of observations can be made. The first is that for an industrial ecosystem to work sustainably it has to be economically viable, environmentally sound and improve the quality of life of those both directly and indirectly involved. The second observation is that although the concept of IE has only really taken off in the last 15 years, industrial symbioses have developed far before. In some industrial ecosystems, such as metal (as well as paper and textiles) recycling cooperatives have existed for decades if not centuries. This points to the fact that industrial symbioses may be a natural process (a view taken in chapters 3 and 4). A third observation is that when a systems view is taken, opportunities arise, such as the closed-looping of material flows and energy cascading, that wouldn't have been perceived if a micro-level view was taken (but see the Kalundborg example). A fourth observation is that, with the exception of Kalundborg, the diverse and diffuse connections, along with a certain amount of redundancy, helps create a flexibility and dynamism in the system helping it to adapt and evolve to environmental changes. A fifth observation, is that although, in some cases of industrial symbioses, the means of production are sustainable the actual resources used or end product is not at all sustainable. A final point is that most naturally developing industrial ecosystems evolve in response to the economic climate, i.e. to gain extra revenues for waste treatment services or to avoid the rising costs associated with waste disposal.

2.9. Problems and Issues

Having now reviewed the history of IE, definitions, models, and real-life case studies, this section highlights a number of criticisms that have been levelled at IE. In particular, weaknesses in the IE framework including the strategies and tools for implementation, a discontinuity between the goals and the strategies and tools, and weaknesses in the conceptual constructs have been highlighted (O'Rourke, Connelly & Koshland, 1996). Industrial ecology, according to O'Rourke et al (1996), is at a crossroads – it can either represent the incremental changes in industry, which are arguably already underway, or it can be the pioneering facilitator for the paradigm shift required for sustainability.

At present, however, O'Rourke et al (1996: 90) view IE as 'a broad umbrella of concepts rather than a unified theoretical construct'. This is highlighted in the definitions of IE in which, they argue, there are too many ambiguous terms used and consequently is too broad and lacks very specific goals, objectives and strategies. Indeed, they observe that 'by drawing the IE box small enough, anything it seems can be an optimised industrial ecosystem' (O'Rourke et al, 1996: 93). However, there is a divide developing between IE researchers. On one side are the advocates who seek incremental changes concentrating mainly on factors for efficiencies, whereas on the other side are the researchers seeking major structural transformations. Until a consensus emerges, ambiguities surrounding IE will persist.

Another problem area for IE is disagreement between researchers as to the usefulness of the biological/ecological metaphor (e.g. Frosch & Gallopoulos, 1989; Ayres, 1994; Graedel, 1996; Boons & Baas, 1997; Commoner, 1997; Ehrenfeld, 1997; Frosch et al, 1997; Schwarz & Steininger, 1997; Pizzocaro, 1998; Newman, 1999). It is somewhat ironic that, on the one hand, industrial ecologists are trying to create a paradigm shift from anthropocentrism to an integrated ecosystem whole that includes human endeavour (e.g. Gladwin et al, 1995a; Ehrenfeld, 1997), but on the other hand, argue that natural systems are only a good metaphor for industrial systems, which still essentially separates human activity from natural activity. This issue is explored in more depth in the model developed in chapter 3 and then further refined with Sheffield as the case study in chapter 4.

Further criticisms can be made of IE's very general approach. IE at present fails to recognise the importance of other attributes of industrial systems particularly those associated with decline, an issue also important in terms of sustainable development. Initial conditions for the sustainable development of industrial clusters are particularly significant. Although, presented by Korhonen (2001) in his locality principle, this aspect of industrial development could be further explored in terms of local and global physical and human resources. Furthermore, the human side of the problem is also significant in terms of IE. The same could be said of the lack of emphasis of strategy, innovation and adaptability. The life histories of the organisations, a common topic in natural ecology, is also inconspicuous in the IE literature. As we shall see in chapter 4, generalisation and specialisation as well as mutualisms, co-operative structures and symbioses are all common occurrences as seen in South Yorkshire's industrial history. The last criticism is that IE fails to deal with industrial systems in decline. For example, an ecological understanding of global competition, the effects of diversity, and employment declines, perhaps seen in terms of energy trends, would be very beneficial for policy and decision-makers concerned with the industrial regeneration effort in South Yorkshire. In an attempt to rectify this, the very unique industrial development of Sheffield and South Yorkshire (focusing on steel and the associated sectors) will be used as the case study for the model developed in chapter 4.

2.10. Further Research

From this review of IE, a number of areas of further research may be identified, some obvious avenues in response of the problems and criticism, and others that are not so obvious. Further work is clearly required to solve definitional ambiguities and to refine IE concepts particularly to include those factors, identified in section 2.9, that to date have be ignored or omitted. This would help considerably in reaching a consensus among academics, practitioners and industrialists.

In addition, there is continual debate in the IE literature as to the usefulness of the biological/ecological analogy, whether natural systems are a good metaphor for industrial systems. This debate may also prove to be a rich source of further research.

Indeed, chapter 3 explores this issue in more detail. Ideas are developed that theoretically demonstrate, using ideas from the science of complex systems, that there is a more intimate relationship between natural and industrial systems, homology rather than analogy. The homology idea (i.e. that natural and industrial systems develop and evolve through the very same fundamental principles) is given credibility by the fact that the classic industrial ecosystems discussed in the literature, e.g. Kalundborg, Styria and the steel industry in Massachusetts in the US, all developed naturally with no external pressure from the public, environmental groups or politicians. As outlined in section 2.9 (Problems and Issues) IE also has a very general scope. Further research is needed that takes account of the idiosyncratic development of regions to add richness and depth to the models of IE.

2.11. Conclusions

Since the 1960s, when awareness of environmental and social problems around the globe dramatically increased, the state of the debate has matured considerably and there is now some consensus on definitions, of contexts, of the most pertinent problems across the globe, nations and regions, and the progress and strategies that need to be made and followed.

What is of importance however, are that problems and issues which people face in different countries and regions are different in either nature and/or scale and thus action and intervention can only be initiated locally. This was demonstrated with the analysis of problems confronting the world and the nation. Although UK environmental problems are very related to global problems, many are not as acute and are now being remedied. The most obvious differences between global and UK problems concern the social and economic components of sustainable development. The people of the UK have a far better quality of life than most of those in developing countries. Nonetheless, sustainable development is a continuous process and improvements are still necessary.

This is further demonstrated by the current position of manufacturing and industry in general. The industrial process is in a unique position as it often seen as the cause of most environmental and social problems either directly or indirectly, but at the same time the main mechanism for change towards sustainable development, i.e. economic growth. The manufacturing sector is vital, and is the cornerstone for the continued economic health of the UK. Industrial ecology emerged as the leading concept with which to understand and to represent the shifts required by industrial sectors to development that is more sustainable.

Although the idea, principles and even some tools of industrial ecology were around in the 1950s (if not before), it wasn't until Frosch and Gallopoulos's (1989) landmark article that the collective imagination of both academia and industry was caught. Since then, the literature regarding definitions, models, case studies, and strategy and tool development (as well as problems with all of the above), has developed rapidly.

There are now many definitions and although there is no standard definition there are several themes that most have in common. These are:

- That the biological/ecological metaphor is taken
- That a systems perspective must be taken
- That the focus is on energy and materials
- That energy flows are optimised
- That material flows are closed
- That the goal is sustainable development
- That natural and industrial activity have to be integrated
- That the industrial system is of an evolutionary nature.

However, these definitions are arguably plagued by ambiguous terms and are either too narrow or too broad in perspective. Nonetheless, many IE models have been developed including industrial metabolism models, extended metabolism models, and the more popular IE models such as the Type I-III industrial ecosystems. A number of other researchers have broadened the ecological analogy to involve phenomena such as energy transitions, diversity, locality, and gradual change. An important typology has been developed categorising five qualitatively different types of IE models – each type having different implications for the organisation under study. The perspectives of these types are:

- The product life cycle
- The material life cycle

- The geographical area
- The sectoral analysis
- A conscious ignorance of boundaries.

Revealing case studies are also available. The most popular of these are the Kalundborg industrial symbiosis in Denmark, the Styrian recycling network in Austria and the metals-manufacturing recycling system in Massachusetts in the US. Important observations of these systems include that they developed naturally with no external pressures and were essentially economically driven. Some criticisms levelled at these systems are that they foster a degree of rigidity, which could stifle innovation and reduce adaptability and resilience. This is embodied in the physical, hard-pipe connections characteristic of the Kalundborg system. Other systems such as the Styrian and metals-manufacturing system are, in contrast, characterised by diffuse and diverse connections which should prevent rigidity. Another important criticism is that although the means of production is developing along the principles of sustainability, many of the resources used and the end products are far from sustainable. This is particularly evident in both the Kalundborg and Styrian systems where the core companies are power plants, chemical industries and oil refineries or dealers.

Further research that was identified concerned the development of models that have an underlying framework from the science of complexity.

CHAPTER 3 - MODEL 1: THE PHYSICAL FUNDAMENTALS OF SUSTAINABLE COMPLEX SYSTEMS

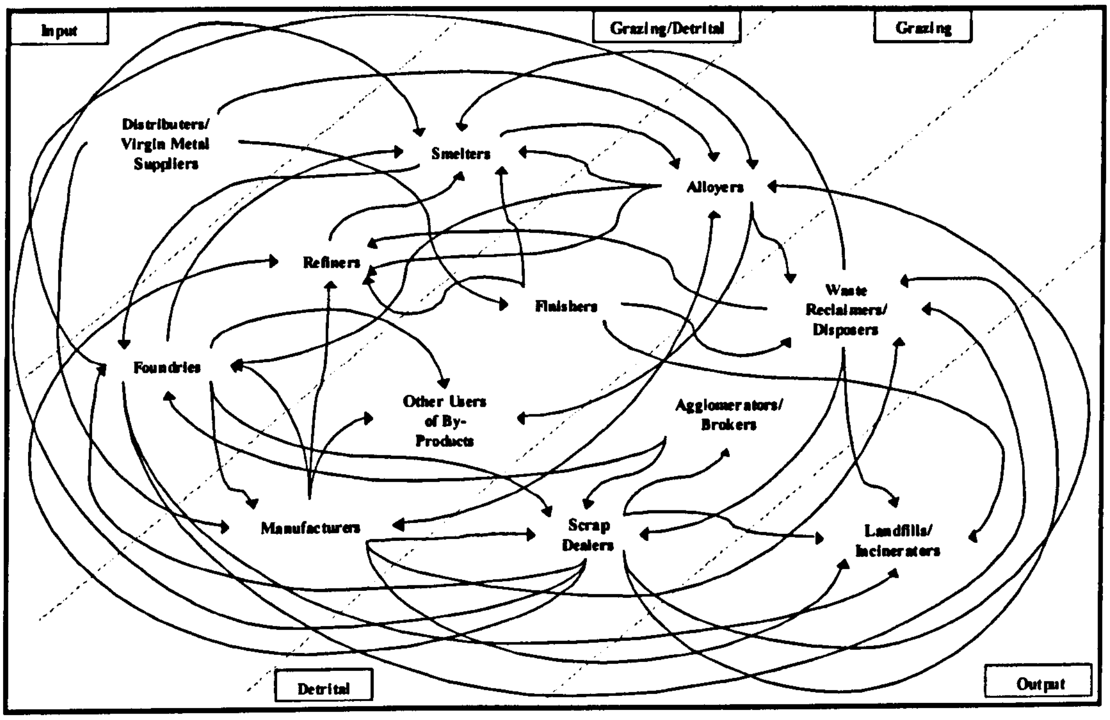
3. Introduction

This chapter consists of an exploration into the physical fundamentals of sustainable complex systems and aims to extend the debate in industrial ecology by proposing a more intimate relationship between natural and anthropogenic systems – homology rather than analogy. This chapter presents the author's theoretical model of the sustainable development of complex systems. This is one of the main outcomes of the thesis. The aim of this model is to develop a generic framework with which to understand more specific cases of industrial development and regeneration of a region, in this case Sheffield and South Yorkshire. In addition, hypotheses such as energy flows, diversification, life histories and climax may be tested (see chapter 4). The ideas developed in this chapter also contribute to the aim, as highlighted in the first chapter, of employing manufacturing classifications (see chapter 5), which takes a micro-level analysis and utilises techniques from the biological sciences.

The motivation behind the framework developed in this chapter is Sagar and Frosch's (1997) presentation of the closed-looping behaviour of a metals-manufacturing system. Of particular interest, is that the system closed its materials cycle without any major intervention from politicians, industrialists or environmentalists. Through reviewing the relevant literature in the science of complexity, this chapter proposes the author's generic arguments that the sustainability of systems is a natural phenomenon. Using theories and concepts from non-equilibrium thermodynamics and complex systems thinking it is shown through a theoretical model how metabolising complex systems arise; that they self-organise and function to degrade gradients or energy potentials; that competition and co-operation are important processes in deriving more complex order; and, finally, how the system sustains its function.

In 1997, Sagar and Frosch (see also Frosch & Gallopoulos, 1989; Frosch et al, 1997) presented a model of the closed looping metabolic behaviour of a metals manufacturing system (see figure 3.1). This system had arguably reached a certain level of sustainability (i.e. the sustained production of metal-based products) and had evolved naturally - this industrial ecosystem developed without any major intervention from the industrialists involved, politicians or environmentalists; that is to say, development proceeded through local activity without any 'global blueprint'. The main purpose of this chapter is to attempt an explanation of this phenomenon using emerging theories and concepts from non-equilibrium thermodynamics and complex systems thinking. Complex systems are, literally, facts of everyday life. Examples are everywhere - organisms, ecosystems, business enterprises, industries and cities. However, it wasn't until the work, in the 1960's, of Ilya Prigogine that a formal school of thought emerged and these interesting phenomena were finally accepted and subjected to rigorous scientific inquiry and application.

Figure 3.1. The closed-looping of metals manufacturing (from Sagar & Frosch, 1997)



In order to establish arguments for the physical fundamentals of sustainable complex systems a number of objectives need to be achieved. Therefore firstly, the roots or the historical account of the emergence of complex systems thinking will be highlighted - Newtonian mechanics, classical thermodynamics and contemporary schools of complexity thought. Secondly, specific concepts such as gradient degradation, the ordering processes of natural selection (competition and co-operation) and autopoiesis will be examined. With examples from a number of systems ranging from simple hydrodynamic systems to highly complicated ecological systems, these concepts will be shown to constitute the fundamental principles with which sustainable complex systems of a physical nature can be understood.

3.1. Introduction to Complexity

The emergence of the science of complex systems has a long and interesting history, the roots of this thinking tracing back to the publication of Newton's (1687) *Principia*. Complex systems thinking emerged in direct response to the limitations of Newtonian mechanics and the reductionist approach (Jantsch, 1980).

3.1.1. Newtonian Mechanics

Principia marked, for what many consider, both the beginning of contemporary scientific inquiry and the pervasive and dominant reductionist philosophy. This work introduced, defined and examined three laws of motion (inertia, acceleration, and counterforce) and applied the perspective to planetary motions. The three laws argue that a body's trajectory, its position and velocity through space, is lawful, deterministic and reversible (Prigogine & Stengers, 1987).

The argument inevitably emerged that the Universe and everything therein were purely mechanistic and linear and still has a strong foothold in thinking today (Kauffman, 1995; Lewin, 1999). In the early 19th century, the newly developing field of thermodynamics, however, was to eventually challenge Newtonian mechanics. Thermodynamics is the science of the balance and flow of energy in nature with a particular focus on both the macroscopic behaviour of matter and the concept of irreversibility.

3.1.2. The Four Laws of Thermodynamics

During this period the four laws of thermodynamics were formulated – the Zeroth law and the First, Second and Third law. The *Second Law*, the third of them, was devised first; the *Zeroth Law*, which is the first, was devised last with logical hindsight; the *First Law*, second; and, the *Third Law*, which is the last law, was formulated in chronological third and regarded by some not even to be a law (Atkins, 1984). Both the First Law, but particularly the Second Law were to be the most profound and, perhaps inevitably, completely revolutionised systems thinking. The Second Law, specifically the entropy principle (discussed below), provided the basis for complex systems thinking in contemporary times.

The Zeroth Law was formulated around 1930 and is concerned with, and provides the basis for the concept of temperature. This law may be stated as (Atkins, 1984; Dugdale, 1996):

> If two systems are put in thermal contact with each other and there is no net flow of energy between the two, the two systems are in thermal equilibrium with each other.

The First Law of thermodynamics was based on the work of Joule (who introduced the concept and quantification of energy), Helmholtz, von Mayer, and others, and can be stated as follows:

> All energy forms, for example, mechanical, chemical, heat, are all interchangeable, but the total energy can neither be created nor destroyed,

i.e. the *conservation of energy* (the energy principle).

Joule's idea of the conservation of energy can be seen in this statement (cited in Kondepudi & Prigogine, 1998: 32):

> 'The phenomena of nature, whether mechanical, chemical or vital, consist almost entirely in a continual conversion of attraction through space [potential energy], living force [kinetic energy] and heat into one another. Thus it is that order is maintained in the universe - nothing is deranged, nothing ever lost, but the entire machinery, complicated as it is, works smoothly and harmoniously'.

The formulation of the Second Law of thermodynamics was perhaps in response to, or catalysed by, the invention of the first steam engine (James Watt being a notable name), or perhaps more precisely, the maximum rate of efficiency the engine could muster - the lifework (albeit short) of Carnot (1890). This work dealt with the efficiency and limitations of the steam engine or, more fundamentally, the discovery of the intrinsic inefficiencies in converting heat into work. Carnot's work went unnoticed long after his death until Emile Clapeyron, a French scientist, brought it to the attention of the scientific community.

In response, two equivalent statements of the second law were formulated, at roughly the same time, both of which identified the fundamental dissymmetry of Nature. Clausius, in 1850, stated (cited in Dugdale, 1996: 33):

> 'It is impossible for a self acting (cyclic) machine, unaided by any external agency, to convey heat from one body at a given temperature to another at a higher temperature'

i.e. heat flows spontaneously only from hot to cold and not vice versa.

Kelvin, in 1852, stated (cited in Dugdale, 1996: 33):

> 'It is impossible, by means of inanimate material agency, to derive [continuous] mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects',

i.e. in any conversion between heat and work, some heat must be discarded into a cold sink (see, for example, the 'Carnot cycle', Atkins, 1984; Dugdale, 1996).

The Third law, formulated by Nernst in 1906, is concerned with properties of matter at low temperatures and is closely coupled with the concept of entropy. It may be stated as follows (Atkins, 1984; Dugdale, 1996):

> Matter cannot be brought to an absolute zero temperature in a finite number of steps and (although controversially) at absolute zero temperature the entropy of all systems [see below] and of all states is zero (or any other arbitrary value as long as it is same for all systems).

It can be seen from this statement that, in contrast to the other laws, the underlying assumption is that matter is atomic. The other laws make no such assumption. This is where the controversy lies, that this law is not a law in the same sense as the others (Atkins, 1984).

3.1.3. The Entropy Principle

It wasn't until thirteen years later that Clausius, in an attempt to unify his statement with Kelvin's statement, expanded the formulation and included the concept of entropy, i.e. that natural processes are accompanied by an increase in the entropy of the universe (the entropy principle). Entropy may be mathematically expressed as:

$$E = F + TS$$

where E is the total energy, F the freely available energy, T the absolute temperature in K° (Kelvin scale), and S the entropy (Jantsch, 1980). The entropy of an isolated system is always attracted to its maximum, a state of thermodynamic equilibrium. When entropy is maximised, all impinging gradients or field potentials are minimised. Thus the Second Law may be stated as entropy maximisation or field potential minimisation (Swenson, 1992). One important point is the realisation of irreversibility, directedness and history of the (isolated) system's processes, that is, the entropy of future system states must be higher (or equal), and that past states can only be lower (or equal). Entropy is the product of irreversible processes (Jantsch, 1980).

Isolated systems evolve through self-organisation, or more precisely devolve through self-disorganisation towards its equilibrium and most probable state. For example, the instant a drop of ink enters a bowl of water, a field potential or gradient is created and the entropy of the system is low. The entropy increases as the ink naturally (in line with the Second Law) spreads throughout the medium until equilibrium and maximum entropy. It is highly improbable that the system's entropy will again decrease and the ink reach its original high concentration. Clausius realised that the Second Law was applicable to all isolated systems and speculated on the fate of the Universe. This led some to the conclusion that the Universe is slowly running down to thermodynamic equilibrium with no capacity left to change - a state of complete randomness.

More or less at the same time, however, Darwin's (1859) theory of the '*origin of the species by means of natural selection*', which shared the concept of irreversibility (i.e. that evolving complex systems move only forward and prior states/conditions are forever lost) completely contradicted this end result. The theory is characterised by increasing complexity or order and decreasing entropy/disorder. The difference between the two stands is that classical thermodynamics investigates equilibrium systems or near-equilibrium systems that are *isolated* or *closed*, respectively. Darwin's systems of interest were *open* to, and had the ability to interact with external sources (to import energy and/or matter) and sinks (to export the waste and heat).

Barlow and Volk (1990) argue that open systems *exchange both energy and matter with the external environment*; that closed systems *exchange only energy* or *matter*; and, that isolated systems *exchange nothing with the external environment*. With the ability to interact with external sources the system may reach a state far-from-equilibrium and phenomena appear, that is, self-organised dissipative structures, that cannot be explained by classical thermodynamics (Prigogine & Stengers, 1987).

3.1.4. Complex Systems Thinking

The works of Prigogine (e.g. Prigogine, 1973), colleagues (e.g. Glansdorff & Prigogine, 1971; Nicolis & Prigogine, 1971; Prigogine & Stengers, 1987; Nicolis & Prigogine, 1989; Kondepudi & Prigogine, 1998) and others (e.g. (e.g. Jantsch, 1980; Allen, 1982; 1984; Allen, Sanglier, Engelen & Boon, 1985; Haken & Mikhailov, 1993; Allen, 1997) have demonstrated how dissipative structures, of qualitatively different kinds, self-organise through the emergence of fluctuations and instabilities within the system. Indeed the theory of 'order through fluctuation' is a central theme throughout their work. These fluctuations may lead, at a critical point, to autocatalytic positive feedback and irreversible bifurcations. This, in turn, may lead to new qualitatively different system states demonstrating a certain amount of stability.

The class of thermodynamic systems are those that are open to energy and/or matter, which constitute the system's metabolism, and are held far-from-equilibrium, maintaining their structure, organisation and reduced entropy through such metabolism. By way of not violating the Second Law, the decrease in entropy in the open system is at the expense of an increase in entropy in the universal system in which the open system is embedded (Toussaint & Schneider, 1998). Through the work of Prigogine and Stengers (1987), this may now be formally stated as:

$$dS = deS + diS$$

where dS is the universal system's change in entropy, diS is the internal production of entropy, and deS is the entropy exported (during the flow/exchange) to the environment. In line with the Second Law, the internal component is either greater than or equal to zero, the external component, however, can be either positive or negative. From this, it is apparent that order may only be maintained in a non-equilibrium state (Jantsch, 1980; Toussaint & Schneider, 1998).

The work of Schneider and his colleagues (e.g. Schneider & Kay, 1994; Toussaint & Schneider, 1998), however, focus on quite different aspects (although acknowledging and building on the work of Prigogine and others) that are more relevant to this discussion. Their work constitutes one of two important elements when considering both the fundamental principles of sustainable complex systems, and sustainable industry as seen as a complex system.

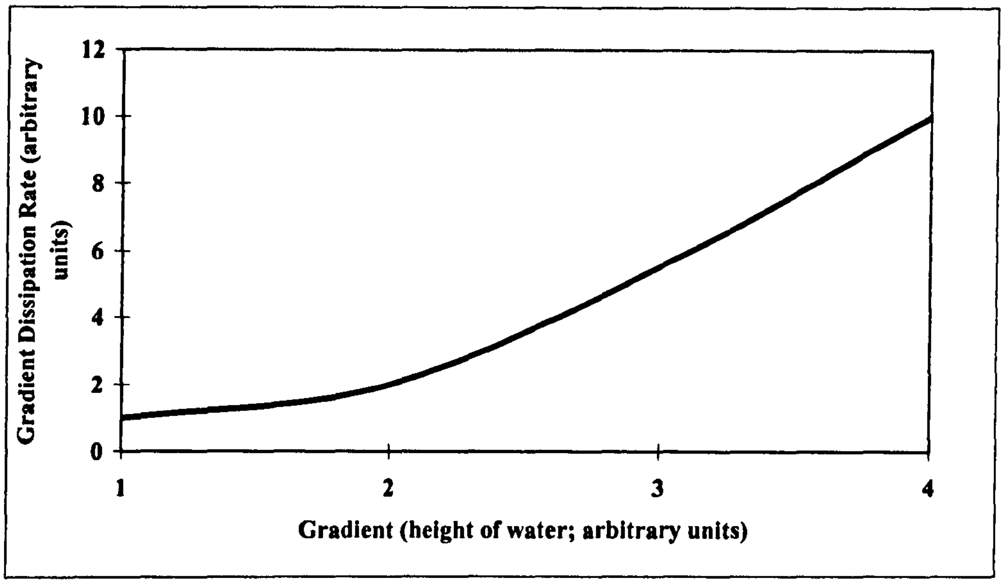
3.1.5. Gradient Degradation

Schneider and Kay (1994), following on from the work of Schrödinger (1944), Hatsopoulos and Keenan (1965), and Ketsin (1968), have proposed a 'restated' Second Law in an attempt to capture some essential properties of the behaviour of such systems (see also Toussaint & Schneider, 1998). The following points can be made. Firstly, thermodynamic systems in equilibrium resist being moved away from their equilibrium state. The second point, is that when gradients are applied that push the system from equilibrium, the system, in trying to reach its local equilibrium attractor, will attempt, using all available avenues, to minimise the field potential or reduce/degrade the gradient. Thirdly, the effect of the system's local equilibrium attractor increases as the applied gradient increases. The fourth point is that other attractors may emerge in which the system may organise to degrade the gradient. And finally, conditions permitting (i.e. kinetic and/or dynamic), self-organisation may occur - indeed is expected to occur. Thus, within this perspective, dissipative structures do not only dissipate matter and energy but also dissipate gradients or field potentials and may emerge wherever gradients are applied.

3.1.6. Gradient Degradation and Natural Selection

An example of the way in which a system may self-organise is the '*Tornado in a bottle*' sold as toys (Schneider & Kay, 1994). The toy consists of two 1.5 litre bottles, the openings of which are connected by a simple plastic orifice. When placed vertical with the top bottle full of liquid and the bottom bottle empty, and without perturbation, the system is incoherent (i.e. obeying random statistical laws) and takes approximately 6 minutes to reduce the gradient (i.e. the water falling from the top to the bottom bottle). If the experiment is repeated and the system is given a slight rotational perturbation, a vortex forms, i.e. the macroscopic ordering of 10^{23} or more molecules. The interesting point of this is that while the incoherent system took 6 minutes to reduce the gradient (gravity), the coherent system reduced the gradient in 11 seconds (Schneider & Kay, 1994). In addition, as the initial gradient, the height of the water, increases, the system's ability to dissipate the gradient also increases (see figure 3.2).

Figure 3.2. Idealised effect of gradient on gradient dissipation rate (adapted from Schneider & Kay, 1994)

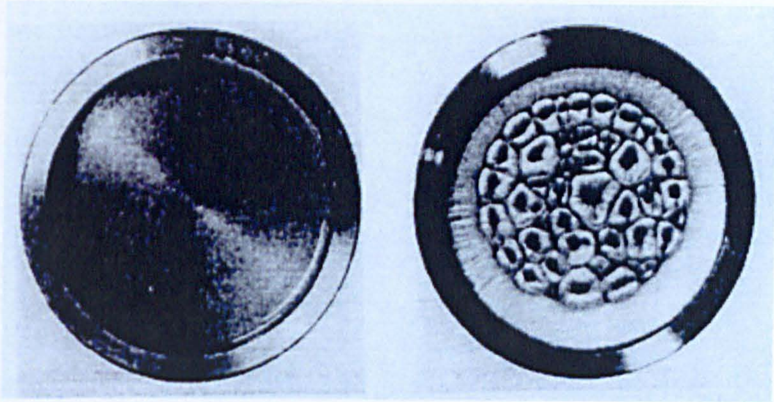


Another oft quoted example of the gradient reducing nature of spontaneous macroscopic order is an experiment performed by Henri Bénard in 1900 in the field of hydrodynamics. If a shallow dish, for example, of approximately 1cm deep liquid is held between a source (heat) and a sink (the colder air above) and is heated uniformly from below, a coherent behaviour pattern - regular hexagonal cells or a honeycomb pattern - emerges abruptly at a critical point in temperature.

The pattern is the result of the gradient in temperature between molecules at the surface and the bottom, and gravity's effect of pulling the cooler surface molecules down to the bottom of the medium. In the systems initial state (before heating), temperature is uniform, i.e. in thermodynamic equilibrium, and the molecules are moving randomly throughout the medium.

As the temperature is applied and the gradient increases, heat is dissipated via conduction. The molecules begin incoherently vibrating, without moving far from their place, and increasingly collide with other molecules which transfers the heat - the system begins to move from an equilibrium state. As the temperature gradient increases, thermal non-equilibrium increases and instabilities or fluctuations emerge in the form of convection streams (i.e. the transference of heat through the coherent movement of molecules), which question the system's structure (i.e. dynamic regime). The system at first responds in the form of negative feedback which dampens or suppresses the instabilities. At a critical temperature gradient, however, the negative feedback switches to positive feedback reinforcing the fluctuations and the process structure, in an instant, self-organises from conduction to convection (see figure 3.3). The collective co-operative behaviour of 10^{23} or more molecules characterises the system (Jantsch, 1980).

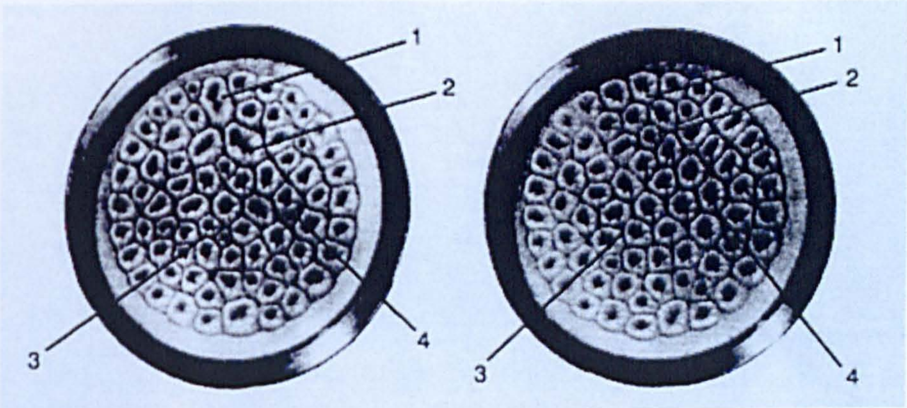
Figure 3.3. Bénard cell experiment: Coherent behaviour (from Swenson, 1992)



There are four important points to be made with this example. As the gradient increases sufficiently, global (macroscopic) structure supersedes local (microscopic) structure. As Swenson's (1992: 215) *law of maximum entropy production* indicates 'order produces entropy faster than disorder'. The second point, again, is that the change in the system's dynamic regime is more effective in both dissipating the temperature gradient (Schneider & Kay, 1994) and increasing the generation of universal entropy (Atkins, 1984). The third point of importance is that each pattern has a degree of steadfastness or stability, that is, each pattern, whether at equilibrium or non-equilibrium, resists change up until a critical point in the impinging gradient. When change happens, with respect to the size of the system and the number of components, it is relatively sudden. Similar changes in social systems, which readily come to mind, are the abrupt changes in behaviour accompanying advances in telecommunications, transportation, and energy systems.

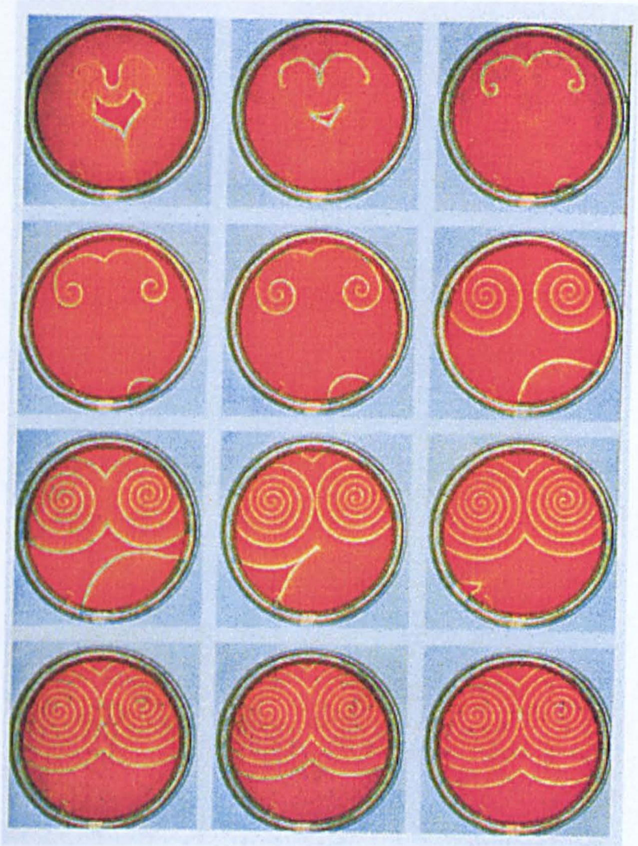
The final point, identified by Swenson (1992), is that some interesting processes occur as the system evolves - phenomena ubiquitous in the natural world as well as social systems. In the Bénard cell experiment, as the system evolves to its state of maximum effectiveness, selection appears to occur at the level of the cell (i.e. the molecular components) and at the level of the system (i.e. the population of cells). Processes such as competition and co-operation appear to take place, both being complementary in the ordering process. The most efficient overall pattern, in terms of reducing the gradient and producing and exporting entropy, is characterised by uniformity throughout the medium in the size and shape of the cells (hexagonal). Just after the transition from the incoherent to coherent, however, the Bénard cells differ in both size (i.e. large and small cells) and shape (i.e. three, four, five, and six sided cells). Processes (see figure 3.4) described as *spontaneous fission* (labelled 1 & 2 in the figure), *subsumption* (labelled 3) and competitive exclusion (labelled 4) are all seen to occur. Spontaneous fission is the division of one larger cell into two smaller cells. Subsumption is where two irregular cells, in terms of size and shape, combine to form one hexagonal cell. Competitive exclusion is where a larger more efficient cell crowds out a small inefficient cell. These are all demonstrable occurrences as the system strives to minimise the field potential or maximise entropy production. They are also common happenings in the economy and other aspects of social systems.

Figure 3.4. The Bénard cell experiment: the selection process (from Swenson, 1992)



These above-mentioned points are also applicable to dissipative structures of both chemical and living systems (Atkins, 1984; Schneider & Kay, 1994) although some further clarification is needed. The most famous and frequently cited chemical system is the Belousov-Zhabotinsky reaction in which an organic compound is catalytically oxidised. If conditions are appropriate, the reaction leads to observable patterns of macroscopic order, in the form regularly pulsating spiral waves - *chemical clocks* (see figure 3.5).

Figure 3.5. Spatial structures in the Belousov-Zhabotinsky reaction system



The oscillatory behaviour represents the spatio-temporal periodic variation in the concentrations of substances. The variation in the temporal dimension represents the generation, degeneration and regeneration of chemical species that defines the spatial dimension with the areas of different chemical species creating the patterns.

The conditions to be met are that the system is open (i.e. that sources and sinks are established, e.g. there is a continuous inflow of starting products and outflow of waste products), that the gradient (i.e. flow of starting products - their oxidising potential) creates a far-from-equilibrium state, and that there are autocatalytic steps in the reaction chain. Autocatalysis is the process where molecules participate in reactions necessary for molecules of their own kind (Jantsch, 1980) and can create both positive and negative feedback (Atkins, 1984).

A simple model was developed by Prigogine and his colleagues, now known as the 'Brusselator' (after the Brussels' School of Thermodynamics), that demonstrated how non-equilibrium systems become unstable and begin oscillating. The reaction scheme is as follows:

$$\begin{gathered} A \rightarrow X \\ B + X \rightarrow Y + D \\ 2X + Y \rightarrow 3X \\ X \rightarrow E \end{gathered}$$

The inflow of species *A* and *B* and the outflow of *D* and *E* are maintained to keep the system in non-equilibrium (Kondepudi & Prigogine, 1998). The autocatalytic step can be seen in the second and third step of the reaction system (where *X* produces *Y*, in the second step, which then produces *X* in the third step). This autocatalysis creates the non-linearity responsible for the emergent patterns (Jantsch, 1980). The emergent patterns and periods of structural instability (which increases reaction rates), in turn, attempt to maximise gradient dissipation or universal entropy production (Kondepudi & Prigogine, 1998).

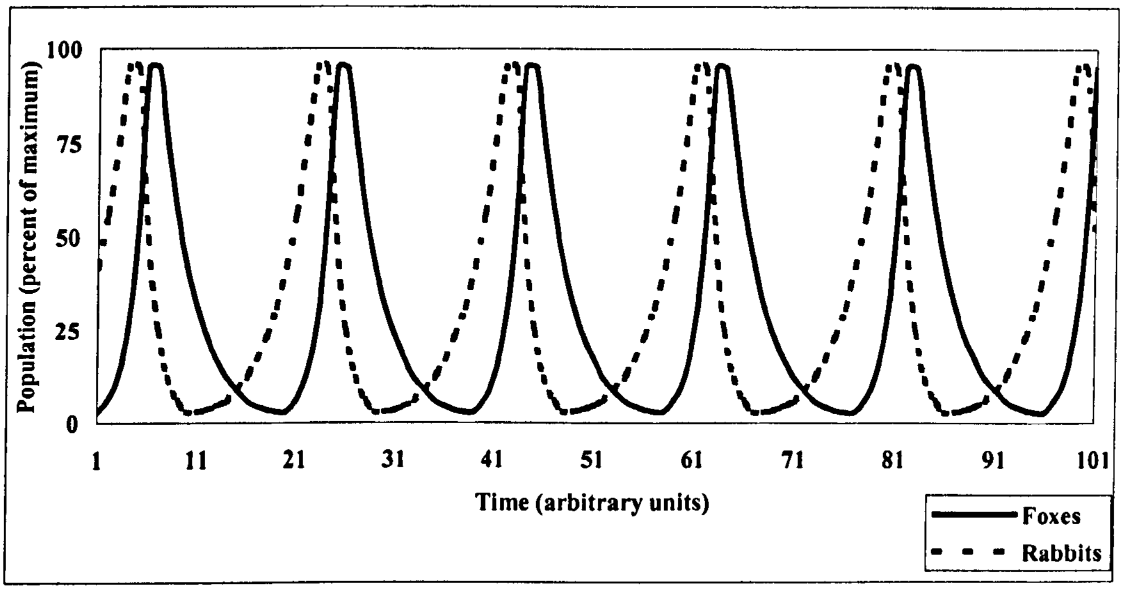
The processes of competition and co-operation (made in the points above), which was readily observable in the Bénard cell experiment, is a little more abstract in these types of systems. These processes lie in the systems oscillatory behaviour. Analogies can and have been made between the oscillatory behaviour in chemical systems (the mixture of reactants and products) and population phenomena in predator-prey systems - the Volterra-Lotka dynamic system (Chakrabarti, Ghosh & Bhadra, 1995) which may be written as (adapted from Jantsch, 1980):

$$\begin{gathered} P + R \rightarrow 2R \\ R + F \rightarrow 2F \\ F \rightarrow D \end{gathered}$$

where *P* is the primary energy and matter (plants - assumed to be constant but limited), *R* is the population of prey (e.g. rabbits) feeding on the plants, *F* is population of carnivores (foxes) feeding on the prey, and *D* are those carnivores that die of old-age or starvation. Autocatalysis is represented by the reproduction cycles of the rabbits and foxes.

As can be seen, all steps are irreversible - rabbits cannot turn back into plants nor dead foxes into live ones. Positive feedback occurs in the rabbit population when there is plenty of plants and few foxes and population growth is exponential. However, the foxes then begin to benefit from more prey and *their* numbers increase exponentially. This creates negative feedback on the prey population, which falls rapidly, then in turn creates negative feedback on the predator population whom begin to die of starvation. The cycle is then repeated and periodic oscillation, as with the chemical reactions, is witnessed (see figure 3.6).

Figure 3.6. Idealised periodic oscillation of predator and prey populations (adapted from Atkins, 1984)



The competition and co-operation in this (very idealised) example can be seen easily at the level of the system, in terms of how the primary energy and matter, the plants, are utilised optimally. Allen (1976) has extended this and demonstrated competition and co-operation at both levels - the individual (in terms of co-evolution - the so called 'armaments race') and the system. The armaments race increases the 'fitness' of each of the species, which is perhaps synonymous with both individual and collective efficiency. One interesting conclusion from Allen (1976) is that the introduction of mutants or new species, and the ensuing process of natural selection, leads to increasingly better use of resources.

3.1.7. Autopoietic Systems: Active Self-Sustenance

Having already established that the primary function of spontaneous self-organising systems is the degradation of gradients or field potentials, and that after having initially self-organised, the system then operates via natural selection (competition and co-operation) to reach the most maximum effective state, it is necessary, when relating to both the physical fundamentals of sustainable complex systems, and sustainable industry as seen as a complex system, to consider a particular class of systems identified by Varela, Maturana and Uribe (1974) - systems that are autopoietic in nature. The term autopoiesis was coined from Greek for 'self-production', meaning that the product of the system's operations is the *system itself.* Systems of this class have relative autonomy, and are self-regulating, self-maintaining, and self-sustaining. Although the three former attributes are important, the latter attribute - self-sustenance - is the central theme of this discussion.

Varela et al, (1974) developed the concept of autopoiesis through their work on living, biological systems and emphasised that the model refers only to the function of living systems. However, a number of authors (e.g. Jantsch, 1980; Zeleny & Hufford, 1992) have found that, while staying within the bounds of the definition of autopoiesis, the term is also applicable to other systems - living systems and systems built upon living systems (e.g. ecosystems and social systems, i.e. the controversial 'super-organisms' - Connell, 1979; Patten & Odum, 1981; Waldrop, 1992; Bailey, 1998; Bonabeau, 1998; Hartvigsen, Kinzig & Peterson, 1998; Levin, 1998). Take for example the autopoietic qualities of a living cell. The cell as a system actively renews its internal components thousands of times during its being, but in despite of this, the system's identity, autonomy, and cohesiveness is maintained. Bertalanffy, an important figure in General Systems Theory, stated that living systems 'are the expression of a perpetual stream of matter and energy which passes the organism and at some time constitutes it . . . a continuous building-up and breaking down of the component materials' (cited in Swenson, 1992: 210).

This may be extended to individual organisms. Analogous to the biological cell, individual organisms renew biological cells hundreds, if not thousands or even millions of times during its normal lifetime. The same can be said of socio-economic systems, for example, it is not uncommon for an individual enterprise to renew its staff entirely within 10 to 15 years. Furthermore, when considering a specific industrial process, say involving hundreds of enterprises in the supply chain, it is also not uncommon to observe many individual enterprises failing or dropping out of the supply chain and new enterprises, with similar functions and processes, emerging constantly. The same can be observed in institutions of law, academia, government and so on. Throughout this constant stream of component change, however, the system in question indeed keeps its identity, autonomy and cohesiveness.

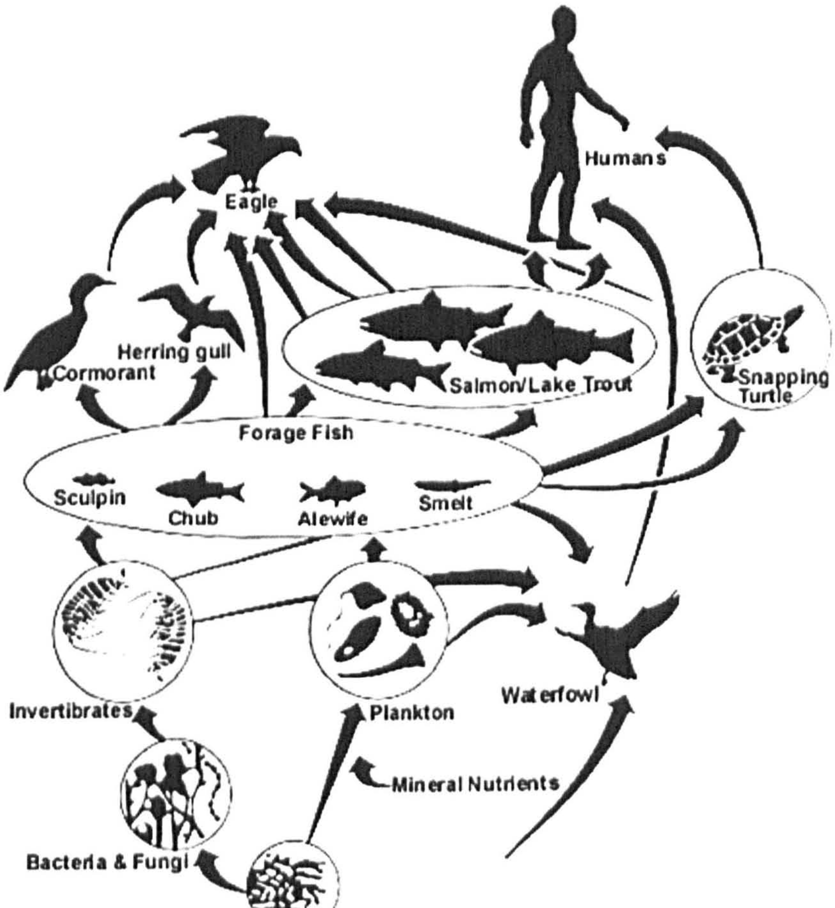
Swenson (1992: 217) similarly argues (although rejecting the use of the word autopoiesis) that a distinction should be made between living and non-living systems, the latter being 'slaves to their local gradients, while the living are not'. Swenson argues that when the local gradient in the tornado and Bénard cell experiments is removed, the dynamic regime ceases and the system reverts, more or less instantly, to its equilibrium state; when the local gradients are removed from living systems (e.g. food) activity often increases (e.g. the search for food). However, this is not true in all non-living systems. Consider chemical reaction systems, when the flows stop, activity continues perhaps for several hours until all energy *stored* in the chemical bonds is degraded (the chemical constituents have reached their most stable state), i.e. until chemical equilibrium is reached.

This is also true of living systems. If food cannot be found, stored energy will be used up, and activity will *ultimately* cease. The important point to be made is that somewhere in the transition from non-living to living, the answer perhaps lying in the prebiotic phase in the evolution of life (see for example Eigen, 1971; Eigen & Schuster, 1977; 1978a; 1978b), the system evolves or develops a mechanism in which a cyclical process of exchange with environment occurs, but more importantly, is *actively* maintained by the system - the evolution of autopoiesis. Energy and matter exchange with the environment creates non-equilibrium within the system, which in turn maintains the process of exchange. The system begins to import energy and matter itself (an active metabolism) to keep it away from equilibrium - perhaps the fundamental characteristic of life

A prime example of this is photosynthesis where energy is actively sought and where gradients are actively set up and maintained primarily for degradation. Another example, is a living cell which imports materials with stored energy into its boundary, uses the energy for its processes and the materials for its components and exports waste materials. Some of the imported materials are transported across the cell's boundary passively, whereas other materials are actively transported across the cell's membrane, a unique feature to living systems. For example, sodium-potassium pumps in biological cells move sodium and potassium against their concentration gradients - non-equilibrium is actively maintained.

This is only one part of autopoiesis, however, the other part is that systems within systems within systems, from the smallest single cell life-form up to the global system, for example, take part in a sustainable cycling of materials (Jantsch, 1980). This is most readily observable in the cyclical nature of food webs in natural ecosystems (see figure 3.7).

Figure 3.7. Closed loop cycling in an estuarine food web



For example photosynthesising species, plants (autotrophs), build up structures through primary energy and matter. All other living systems are dependent on these photosynthetic species. Herbivores then consume the plants, further degrading the energy and incorporating the essential matter into their structures. Carnivores or omnivores then eat the herbivores (and possibly plants), and then higher carnivores eat the latter and so on until the last carnivore that has no predator dies of natural causes. The elements constituting the carcass are then broken down in a similar web in the detrital cycle until the end product is primary matter (the foodstuff of plants) where the energy has been completely degraded - the cycle is then repeated.

This principle, as can be seen by Sagar and Frosch's (1997) work, not only applies to natural systems but to anthropogenic systems including traditional industries such as metals manufacturing (see figure 3.1). Thus, material flow cycles tend to close as systems mature to ensure the continuation of the process of gradient degradation (Schneider & Kay, 1994) - physical sustainability, via natural law, is strived for and achieved.

Sagar and Frosch's argue that the main driving force behind the close-looping phenomenon is purely economics (money substituting energy). In their words they found (Sagar & Frosch, 1997: 44):

> 'that the factors underlying decisions taken by firms regarding metal flows are predominated by economics (to stay in business and maximise profits), regulatory concerns (to allow them to continue operations), and liability considerations (to prevent future economic costs).'

In early development, the structure and organisation of this system consisted of a purely linear process – virgin ore extractors through to the smelters and manufacturers through to landfills (via consumers). As processes became more sophisticated, through innovation and mutation, niches for refiners, foundries, finishers and alloyers began to open up. The interesting part is where it becomes more economical to reuse materials rather than virgin ore as natural stocks decline. This results in the niches in the detrital cycle opening up.

Firms involved in waste reclaimers, scrap dealers, dismantlers, agglomerators and other users of by products represent these niches. Controversially, there would be no need to regulate and penalise. Supply and demand, through selection pressures, ultimately shapes metabolic behaviour. As virgin ore becomes scarcer, other sources become more attractive, particularly sources that were once sinks. Again, much of this infrastructure arguably developed prior to environmental regulation, being shaped purely by economic incentives through supply, demand and increasingly scarcer virgin ore. This is further demonstrated the silver, gold and platinum metabolisms.

Thus, this synthesis of non-equilibrium dynamics, with biology, ecology and the industrial process, comes down to the properties of energy and matter in particular states and conditions. Systems, open to the flux of energy and matter, in certain non-equilibrium conditions, create gradients and may give rise to the emergence of metabolic behaviour. Open systems, in attempting to degrade the impinging energy gradients, utilise the available matter and metabolise it. In doing so, the self-organisation of ordered process structure occurs, gradients are degraded, entropy produced and exported increasingly faster. To keep (or sustain) the degradation of the exergy content of the impinging energy, two pathways essentially develop. One produces and builds complex structures from the material(s) (the grazing pathway in ecology), the other pathway breaks down these structures (the detrital pathway). These pathways are of course extreme cases and largely artificial, in reality species or organisations may lie anywhere between the two extremes.

3.2. Further Research

The novelty of this thinking arguably leads to further research in the field of industrial ecology. One direction would be to build more specific models of industrial development that also take account of unique circumstances such as regional decline. This is pursued in the next chapter. Potential areas for exploration may focus on the degree of homology rather than analogy, that is, examining to what extent the underlying processes of development are the same for natural and anthropogenic systems.

In addition to ascertaining the degree of closed-looping behaviour there is in industrial systems (as is the norm in industrial ecology) other hypotheses may be tested from natural ecology and from the review in chapter 4 of the industrial development of Sheffield and South Yorkshire. Additional hypotheses may include testing the similarities between industrial and natural systems, particularly the well-established trends such as energy through flows, diversification, life histories, and climax.

If these trends do exist in industry it would be particularly useful for not only planning, and decision- and policy-makers, but also to the industrialists intimately involved in such systems. For example, if energy through flow trends in industrial systems mirrored those in natural systems, i.e. energy intensity increases rapidly in early development, peaks, declines for a period, and then plateaus (Odum, 1969), it would explain partially the problems that mature industrial systems, such as metals manufacturing, have faced and still face now.

The argument of homology will also contribute to the justification of employing biological classification techniques to manufacturing organisations. Manufacturing cladistics, an evolutionary classification scheme from the discipline of biology, appears to share the same problem with industrial ecology, specifically the limited use of analogy. By presenting arguments that reconcile natural and human systems, this chapter, along with the model presented in the next chapter, provides a potential solution to this problem. This objective was highlighted in the first chapter and the research on manufacturing cladistics is further discussed in chapter 5.

3.3. Conclusions

This chapter, motivated by Sagar and Frosch's (1997) model of the closed-looping behaviour of the metals-manufacturing system, proposes an argument of a more intimate relationship between natural and anthropogenic systems based on the first principles of physics. The most important points highlighted in this discussion of the physical fundamentals of sustainable complex systems are that:

1. Systems with the ability to establish a metabolism with the environment (an open system) may be maintained at a far-from-equilibrium state which, in turn, maintains the system's structure and organisation
2. Self-organising systems are in response, and function primarily, to degrade gradients
3. As a new system steady state is reached, immediately after self-organisation, processes of competition and co-operation, complementarities in the ordering process, take place, as the system strives to degrade the gradient and produce and export entropy in the most effective manner possible
4. Living systems and systems built upon living systems are autopoietic in nature. That is, non-equilibrium is actively pursued by the system and that systems within systems attempt to close the flow of materials so that the processes of gradient degradation and order production can continue indefinitely.

The above points, therefore, demonstrate *how* complex systems may arise - when the system is open and when a gradient is applied (points 1 & 2); *why* they arise - they function to degrade the gradient (point 2); *how* the maximum effectiveness of function is reached - natural selection (point 3); and, *how* the system sustains its function - autopoiesis (point 4).

Further research identified concerned the development of a model that incorporates the uniqueness of specific industrial regions whilst also demonstrating other similarities between natural and industrial systemic development. This is the subject of the next chapter. The development of manufacturing classifications was also identified. The research on this begins in chapter 5.

CHAPTER 4 - MODEL 2: THE N-ET MODEL OF SUSTAINABLE INDUSTRIAL DEVELOPMENT

4. Introduction

The aim of this chapter is to build on the generic model developed in the last chapter and present the author's non-equilibrium thermodynamic (N-ET) model of industrial development. The perspective is used to develop a better understanding of the general issues involved in sustainable industrial regeneration. Special attention is paid to the South Yorkshire region of the UK as the majority of SMEs are largely mature, low-tech industries that participate in the metals manufacturing industry – one of the oldest industrial ecosystems.

This chapter attempts to both extend the present status of industrial ecology and, as highlighted in the first chapter, to provide a framework for manufacturing classification research based on biological classification techniques. Both these aims are achieved by examining the industrial process from a theoretical framework derived from first principles: Schneider and Kay's (1994) non-equilibrium thermodynamic paradigm of systemic development. What distinguishes the N-ET model from other models presented in the industrial ecology (IE) literature is the extended use of complex systems thinking which leads to the novel argument of homology rather than analogy. The argument of homology bridges the conceptual gulf that exists between natural and anthropogenic systems.

The N-ET model argues that characteristic metabolic behaviour observed in systems, open to fluxes of energy and matter, appear to reconcile physics, biology, ecology, and, with qualifications, the industrial developmental process. Central to the N-ET model is Odum's (1969) general phenomenological synthesis in ecological succession and the characteristic patterns in production and energy flow, metabolism, diversification, organisational life histories and homeostasis. Preliminary support for the model is found in existing databases and literature. The implications of using the model to examine and predict regional decline and regeneration are discussed and areas for further research are identified.

4.1. Case Study: South Yorkshire, UK

The N-ET model was developed to increase the understanding of the environmental, social and economic processes (WCED, 1987; UNCED, 1992; DETR, 1999a; 1999b), involved in sustainable industrial regeneration. South Yorkshire, in the UK, is taken as the model case study. This is because there is now a desperate need to regenerate and sustain the regional manufacturing industry. After a well-documented industrial decline surrounding metals manufacturing (e.g. Tweedale, 1995), South Yorkshire faces many serious problems. One of the most prominent problems is a 26% decline in employment giving it the 4th highest unemployment and 5th highest long-term unemployment rates in the UK. With the decline of a mature industry, the existing workforce now have out-dated skills. There is also little tradition of entrepreneurism coupled with a low rate of new enterprise start-up. Existing enterprises typically have low levels of research and innovation and a lower use of technology. With reluctance from outside investment, industry remains vulnerable with structural weaknesses in the economy. This is demonstrated by an under-representation of high technology and growth services (SFP, 1999b; 1999a).

The second reason is due to the fact that the European Community decided to award the area Objective One status. With this status, funding is provided to boost the region's economy by £912m by starting new businesses, training young people and creating 35,000 new jobs. The overall aim is to enhance the sustainable development of the region. However, there is no discernable overarching strategy or model to distribute this funding. The model, therefore, may be used to guide policy decisions and to direct funding in more appropriate target areas.

Before this however, an introduction is needed outlining the development, clustering phenomenon and decline of the metals-manufacturing system. The review aims to present an alternative perspective of the typical IE description of industrial development and to identify weaknesses in the representations of industrial ecosystems. The review includes an account of the importance of initial conditions encompassing the local physical and human resources, the growing market demand, and the structure and strategy of the industry and its facilitation of innovation and adaptability.

4.1.1. Sheffield Steel: The Clustering Phenomenon

> 'Sheffield's network of steel-related industries produced something unique. To be sure, one can point to other nineteenth-century steel centres, such as Pittsburgh, which to a certain extent mirror Sheffield's spread and complexity within a relatively concentrated locality. More recently, some European clusters – such as the Lumezanne valley in northern Italy – have become successful in metal manufacture by drawing on the potential created by the distinctive relationships existing between groups of firms. In computer-related technologies, California's Silicon Valley and Greater Boston's Route 128 have become the most spectacularly successful of all industrial concentrations. But none of the foreign metal-working clusters ever quite emulated the wide range of industries in Sheffield nor the richness and depth of its historical tradition; while it may be many years before we know whether the computer clusters have proved as enduring as Steel City. For over 200 years after the discovery of crucible steelmaking, Sheffield was the leading special steel and toolmaking centre in the world, maintaining its position by a strategy that focused on high-technology, added-value, specialist products, and combining this with an unceasing effort to innovate and upgrade factors of production.'
>
> *(Tweedale, 1995: 407-9)*

4.1.2. Initial Conditions: Physical Make-up of South Yorkshire

The physical make-up of the early Sheffield region present somewhat of a paradox – the surrounding landscape had several important, if not essential, advantages, but also some severe restrictions (Tweedale, 1995). The first major advantage, particularly in the system's early development, is the abundance of hills and streams (Holland, 1824; Crossley, Cass, Flavell & Turner, 1989). Sheffield is at the point of convergence of five rivers totalling thirty miles on which the remains of 115 water mills have been found. The intensity of Sheffield's industrial water-use has arguably no comparison. Iron ore, although of low quality, was in abundance and could be mined locally. The region was also heavily wooded, providing the charcoal that was essential for adding the carbon content in steel. Later when coke replaced charcoal, with the introduction of the Huntsman process, Sheffield's situation became even more fortunate, lying on the edge of a massively abundant coal seam.

Other materials, that became essential later in Sheffield's development, were also readily at hand (Tweedale, 1995). Sandstone, used for grinding; ganister, or 'firestone', that lined the furnace-chests and holes; clay that made up the crucible pots, the quality of which was hard to find in other regions such as America and the continent; and silica, for firebricks.

One major, and perhaps underestimated, factor of Sheffield's early pre-eminence in crucible steelmaking was their special agreements, reinforced with long-term contracts, with Swedish iron manufacturers. Swedish bar iron was the purest iron that could be found at the time and for some time to come. Sheffield's monopoly was greatly helped with their exclusive supply of the highest quality iron grades such as 'Hoop L', 'Double Bullet', Gridiron', and 'W and Crown'.

One factor, however, that should have had a negative effect, constraining rather than enabling development, was that Sheffield was 'one of the most land-locked towns in the country and one of the most difficult to reach along the nation's highways. A remarkable feature of Sheffield's industrial growth is its success in over-coming these handicaps' (Hey, 1991: 9). Indeed, it appears that the other physical factors (as well as the resourcefulness and influence of the local people) were so advantageous that the communication problems were soon solved with the introduction of roads, canals and railways. As can be seen, the local physical conditions and the close locality of many of the resources, with the exception of communications, played a very important role in the success of the region. The communication problems reinforce the view that local resources were paramount in Sheffield's early development.

4.1.3. Initial Conditions: Human Resources, Skills and Traditions

The skills, attitudes, and knowledge-base represents perhaps the most powerful resource and is at the very heart of regional development. Being rural in nature (see, for example, Hunter, 1869), cutlers were skilled in every aspect of the craft, and cutlery and hand-tools were wrought by hand from sheets or bars of iron and steel.

Another feature of the initial conditions were the multifaceted skills needed in the already remarkably diverse craftsmanship of both cutlery and hand-tools. The 2000 or so grooves in a file, for example, which needed to be of varied depth, angle, and spacing, were achieved by chisel and hammer at a rate of up to 80 grooves per minute. The same can be said of the skill needed for pocketknives some of which, for showcase purposes, had over 2000 blades, scissors, and other implements.

Skills in melting and forging, fostered from the ancient charcoal iron industry (Roman times), appear to be an essential prerequisite for the modern steel industry. For example, the Huntsman's process for making crucible steel, a process no other region could master, demanded not only physical strength but also a 'skilled eye'. This 'rule of thumb' empiricism initially begat the need for science, and since an experienced melter, according to Harry Brearley (the discoverer of stainless steel), could detect 'a variation in hardness corresponding to a fiftieth of one percent of carbon it may be concluded that this means of observation was developed to an extraordinary extent. It became in fact an art' (Brearley, 1995: 38). Crucible steel making reinforced the skills and knowledge-base and extended Sheffield's already formidable expertise.

Another feature that has some bearing on future developments (and also in the demise of cutlery), and in part derives from centuries-old skills and knowledge, are the peoples' apparent independence and rebelliousness that manifested in two forms – a religious non-conformity and trade-unionism. During the late 18th and early 19th century the unions were very instrumental. Apprenticeships were regularised, aiding the smaller enterprise; member's standard of living appreciably improved; benefits for sickness/unemployment were organised; Saturday half-holiday was established (one of the first regions in the UK to do so); and education was promoted, with the pioneering of the People's College (1842) and the funding of classes at the Mechanics Institute (Chapman, 1955).

4.1.4. Market Demand

Sheffield's timing with the early industrialisation of the western world, providing the demand for tools and other civilised accessories, was almost perfect. Crucible steelmaking, with Sheffield's monopoly over Swedish iron supply, could not be replicated in other parts of the world. By 1750, the trading of hand-tools, cutlery and tool steels had become worldwide, with interest from Sweden, France, Germany, Switzerland and, most importantly of all, America. The domestic market was also important with crucible steel making impacts not only in cutlery and hand-tools but also for the machinery in other industries, in surgical instrument makers, pen makers and in agriculture.

The American market, however, was by far the most important (Tweedale, 1987). Tweedale (1987) argues that the intensity and length of the relationship between Sheffield and America belittled any other Anglo-American bond. The Sheffield-American interdependence began around the mid- to late-eighteenth century and lasted well into the 20th Century, although it began to decline by the 1860s. Before 1860, America proved to be the largest source of income. In some years America accounted for between a third and a half of Sheffield's output. This market, with the rapidity of the Sheffielders' response, as well as the difficulties in producing crucible steel, are the main reasons for the region's speedy expansion and then domination of the steel industry. Between 1840 and 1860, the number of melting holes almost doubled from 1,333 to 2,437, whilst output, which stood at 20,000 tons, quadrupled to 80,000 tons.

4.1.5. Strategy and Structure: Innovation and Adaptability

The process of innovation, arguably a property of both the intense clustering of the industry and the ease of entry into the trades, is a very interesting phenomenon. The intense clustering and the extensive networks established (encompassing local financiers and banks), gave the ordinary worker the opportunity to enter and prosper in either the cutlery, hand-tools, or crucible industries, with relatively little risk (Lloyd-Jones, Lewis & Gore, 1994). The dense networking appears evident not only within particular trades, but also between trades, particularly the related and supporting industries. The result being a highly interconnected and interdependent and yet vastly diverse regional manufacturing system (Keeble, 1997) – the core material of which was steel.

Although Sheffield's early industrial structure was not as differentiated when compared to other manufacturing centres such as Birmingham, the trades related to the steel core, however, were highly diverse and considerably interconnected and interdependent. These allied trades ranged from cutlery and tools, to button making to small metal boxes for tobacco and snuff to surgical instruments. As early as 1824, there were over sixty of these supporting industries. In addition, there were firms specialising in acid etching, pearl, ivory, horn, glass, gold, silver and paper (for packaging), all of which stem from the demand from cutlery. There were also organisations dealing with clay, charcoal, coal, coke, ganister and silica. Iron manufacture was also still prominent particularly for the manufacture of engineering and agricultural tools and for the railways. These trades mostly dealt with the domestic market, mostly with Sheffield. Some, however, were beginning to trade internationally, especially the 'Sheffield Plate' manufacturers, and the manufacturers of engineering plant, castings and wire.

One major determinant behind Sheffield establishing a superior competitive advantage was company structure and strategy. Table 4.1 shows the employment in the main divisions in the cutlery trades. These, however, were extensively subdivided again into mainly individual production units or independent craftsmen – 'outworkers' were the characteristic feature of the industrial structure benefiting both the manufacturer and outworkers coping with fluctuating demand and diverse product range.

Table 4.1. Employment and divisions in cutlery (adapted from Tweedale, 1995)

Table knives	2,240
Spring-knives (pocket knives)	2,190
Plated trades	2,000
Files	1,284
Scissors	806
Edge-tools	541
Forks	480
Razors	478
Saws	400
In the country	130
Total	10,549

There were also large firms, most notably Joseph Rodgers & Sons and George Wostenholm & Son. But these larger firms, although succeeding in some economies of scale, still reflected the industrial structure in that they still used the outwork system and, despite having large factories, the labour was still highly divided. Indeed, a journal named *Penny Magazine* (168), in 1844, when speaking of Joseph Rodgers & Sons' organisation stated (cited in Tweedale, 1995: 50):

> 'It would be impossible to trace the manufacturing history of a knife without following it to other workshops in Sheffield. And such may be said of the larger firms generally, as well as the smaller ones. Each class of manufacturers is so dependent on the others, and there is such a chain of links connecting them all, that we have found it convenient to speak of Sheffield as one huge workshop for steel goods.'

The development of this industry was far later than the cutlery and tool trades. Whereas cutlery flourished during the 14th century, the beginning of the steel industry was marked essentially by the Huntsman's process. By the 1840s, Sheffield steel dominated the world. In 1787 there were 10 steel producers, by 1817 there were 34 and by 1856 there were 124. Sheffield's share of UK steel production in the 1840s topped 90%. More significantly Sheffield produced half of the world's steel. Interestingly, steel production accounted for only one quarter employment, the other three quarters being employed in the lighter trades (i.e. cutlery and hand-tools).

The industrial structure of steel manufacture highly resembled that of the light trades, a somewhat pyramidal structure. Small firms dominated the scene. This, however, provided a good platform for the few large firms. Although accounting for the majority share of steel production, the large firms did not typify the region. Small-scale enterprise was the main characteristic – some specialised, for example, in just converting or melting, whereas others generalised, for example cutlery firms also converted and melted their own steel.

One overwhelming feature, as with the light trades, was that the industry was almost exclusively family operated. The steel industry also mirrored the cutlery and hand-tool industry in that the firms were highly dependent on their competitors. Although highly secretive and obsessive about reputation, few firms could manage all processes involved in the manufacture of the final product, thus 'hire-work', as with cutlery, was a predominant feature. In fact, some firms functioned purely, and were very successful, on just hire-work.

With both the cutlery and hand-tool, and the steel industry structured in this way, innovation, entrepreneurship and adaptability was the norm. Cutlers, prior to mechanisation and the standardisation of patterns that were their downfall, prided themselves on adaptability and filling very specialised niches. Throughout Sheffield's history, the dominant company strategy, with few exceptions, was focused on innovation, adaptability, commitment to the highest quality, and a highly diverse product base. Later, particularly in the steel industry, there was also a huge commitment to research and development.

4.1.6. Clustering Collapse

The decline of Sheffield steel and related industries may be described as relative and not the absolute 'collapse' that many have described it as. Although Sheffield has lost its dominant place, and been overtaken by, for example, even Brazil, Italy and Spain, it still houses some of the most advanced technological production facilities when compared to other regions. Even at the height of the region's decline, during the 1980s, it was still producing as much steel as it ever had, and this with a fraction of the workforce. Innovation and progress still continues although the majority of innovations are more minor in scale, as one would expect in a more mature industry. High-level research still continues in private laboratories, such as Swindon Laboratories, and at both Universities in Sheffield.

Steel and its related trades, with engineering a major player (Ripper, 1910), still constitute a considerable, if not vital, force in the local economy, with two thirds of the region's top twenty companies in representation. It is perhaps the decline in employment that was, and, to a lesser degree, still is, the most controversial event. To put the decline into context, employment in tool steels stood at 20,000 in 1970, by 1991 it was 1,200. The steel industry in South Yorkshire, with Rotherham having a significant share, employed 60,000 in 1971. By 1994 there was less than 10,000.

The more popular reasons or explanations of regional decline include: that a structural shift from manufacturing to services was necessary, as the country and region had reached industrial maturity; that entrepreneurial activity suddenly ceased; a strong dislike of heavier industry in general had developed; and failures in modernisation, both educational and industrial. Both the Government and industry itself have been heavily criticised. The Government has been accused of lacking in support when proposals were made for independent sector programmes of rationalisation; for contributing to the standoff between public and private concerns; for not protecting domestic industry against foreign competition; and for creating high-energy costs and high exchange rates. Accusations levelled at the industry itself include showing arrogance and complacency towards competition from the Far East; for having dated sales and marketing techniques; for having no co-ordination in investment; and for having a resistance to merge interests.

There is also a general tendency from critics to voice that decline is a relatively recent phenomenon, with cutlery's decline beginning in the 1950s, and other sectors following a decade later. There are good indicators, however, that the roots of decline were evident much earlier, with specific events and periods particularly revealing. For example, the time in which competition from abroad caught up and then overtook Sheffield towards the end of the 19th century. The period between the wars was also significant when it was thought that investment in modernisation and relocation was badly needed. It can be even argued that the demand from both the early American market between 1830 and 1930, especially between 1840 and 1890, and from the Government during the wars, especially the first, had led to somewhat abnormal growth patterns. This explanation is attractive, particularly as the region was at a loss for what to do after the demand from these sources declined.

The impact of the wars and the boom of the 1950s, like that of the early American market, cannot be underestimated. During the wars, Sheffield was heavily involved in armaments so much so that Sheffield steel has often been described as essentially an armaments industry and its commitment to this volatile market is reason enough for decline. At this time, the largest Sheffield firms almost entirely relied on demand for armaments and their strategies and activities were centred on arms production. The effects of the First World War, that is, the rapid growth and expansion of the steel industry, and the war's ending, led to the consensus that re-organisation and even re-location were badly needed. However, these moves were deferred as a trade depression occurred during the wars. The key decisions and actions were further deferred for another half century as a series of events took place and the mentality of 'if it isn't broken, don't fix it!' predominated. The key events included the re-armament programme in the late 1930s, the outbreak of the Second World War, and a boom time for steel during the 1950s' reconstruction. When the industry finally had to face up to re-organisation it was, in hindsight, far too late. The twice nationalisation and de-nationalisation of the steel industry were also significant events.

It is with some irony that some of the reasons for the region's decline are also the reasons for its early success. This is especially evident when considering the wealth of knowledge, skills and tradition the area held. Most sectors in steel are now completely de-skilled. With cutlery and hand-tools more or less completely mechanised, and with the modern precision steelmaking technologies along with the computerisation of control and analysis, which have greatly increased quality and consistency, steelmaking and its related industries can now take place and flourish anywhere. Areas of cheap labour as well as low energy and scrap costs are increasing in popularity. The same can be said of the advantages of South Yorkshire's wealth of water, coal, clay, and other minerals.

Although the global demand for steel and alloys itself looks good for the foreseeable future, Sheffield's role as a major producer comes into question, particularly with both the demand either plateauing or declining in industrialised countries, and with the recent economic structural shift to services. The only sector related to steel that is flourishing at the moment is the aerospace industry and this is only with a significant commitment from Government in defence spending. There is a similar picture in tool steel. Markets are rapidly disappearing in, for example, engineering and agriculture, a direct consequence of both technological advancement and changing social trends. Substitute materials for cutting and machining are also appearing. For example, the introduction of carbides, these can cut or machine one hundred times faster than some of the older tool steels and thirty times faster than some of the more advanced tool steels. The same can be said of cutlery and hand-tools.

The intense clustering of steel and related industries has all but disappeared. The mix of trades, of between 60-70, have either fallen victim to technological change, competition or obsolescence, leaving very few survivors. Even those that have persisted are no longer heavily interconnected and interdependent as before, for example, cutlery and hand-tools no longer rely on locally produced steel, having found substitutes or cheaper imports. Furthermore, the big steelworks that are still in operation, are now 'closed shops' – all processes and stages of production are all largely done on site, nullifying the need for converters, forgers, furnace-builders and so-on. Even heavy engineering, which also experienced a dramatic decline, relies increasingly less on Sheffield steel. The same can be said of the demise of electrical, agricultural, motorcar, railway, and coal engineering. Similar declines in Rotherham, Leeds, Manchester and other important industrial districts, which, with Sheffield formed a huge densely connected industrial network, have further helped in the unravelling of Sheffield's dense cluster.

The complete structure of Sheffield steel had dramatically changed from one that was predominantly family-operated and independent while heavily fragmented, to one that mostly reflected large Plc's with trained managers and scientists, and with control perhaps residing outside Sheffield and even the UK. The highest quality of standards, which Sheffielders' prided themselves on, is now taken as the norm. Trademarks have become increasingly irrelevant and standardisation has suppressed the exploitation of niche markets. In short, the only aspect now worth considering is price. The steel industry of old that had occupied the majority of Sheffield inhabitants is now controlled by relatively few, exceptionally efficient, groups of people.

4.1.7. Sheffield's Industrial History: Conclusions

What is very interesting and somewhat ironic are that many of the reasons for the region's initial success, for example, the physical conditions, the skills, traditions and attitudes of workers, the company strategies of quality commitment (particularly with cutlery and hand-tools), and the industrial structure, may also be cited as some of the reasons for the region's decline. Along with these explanations, it is also apparent that the region's success, or at least its rapid growth and expansion, is due mainly to the perfect timing with the industrialisation of the western world, and perhaps even more so, the industrial development of the Americas. This massive injection of money appears to have fuelled an abnormal growth pattern, further reinforced by the two World Wars and the 1950s boom. It is also evident that some of the profits in all four of the main sectors, that should have been invested in modernisation and adaptation strategies, were taken out of the industry to increase personal gain.

In terms of developing models of regional industrial networks, it is clear that the idiosyncrasies of regional development need to be incorporated. Although models of industrial ecology typically focus on just the recycling of materials, it is clear from the natural ecology literature that there are several more features to ecosystem development (Odum, 1969), which as we shall see, encompass and may explain many of the phenomena of South Yorkshire's history. However, before examining the relationship between natural and industrial systems, a rationale for the argument of homology must be presented. Indeed, the N-ET model of industrial development is grounded in fundamental thermodynamic ideas.

4.2. Fundamental Thermodynamic Ideas

The paradigm of complex systems arguably begins with Schrödinger (1944) who suggested that biological order followed two pathways – *order from order* and *order from disorder.* The first resided in DNA, confirmed by Watson and Crick (1953) a decade later. The much-less-understood second pathway is grounded in thermodynamic principles explaining the fundamental interrelationships between energy, heat-flow and work.

As mentioned in the last chapter, the *First Law of Thermodynamics* states that energy in a closed system is conserved. The *Second Law,* by introducing temporality, stipulates that exergy (the part of the total energy with the capacity to do work) always decreases, and, conversely, entropy increases. Ordered process structures, characterising life, seem to cheat the Second Law. Nonetheless, whereas classical thermodynamics deal with isolated or closed systems in near-equilibrium states, non-equilibrium thermodynamics deal with systems open to both energy and matter. By exporting accruing entropy into the environment, order production is maintained. Life is thus compensated in the overall budget of entropy. Indeed, the *Law of Maximum Entropy Production*, states that order enhances the inevitable increase in Universal entropy and that 'order produces entropy faster than disorder' (Swenson, 1992: 215).

Prigogine and colleagues (e.g. Glansdorff & Prigogine, 1971; Prigogine & Stengers, 1987), with their work on *dissipative structures* and *order through fluctuation*, empirically reinforced this view. Dissipative structures, with their ability to dissipate matter, energy and accruing entropy, typically emerge from fluctuations and instabilities. These emergent phenomena are due to non-linear dynamics inherent in far-from-equilibrium conditions characteristic of system-environment exchanges. Numerous authors have now further deliberated on the applicability of complex systems thinking to socio-economic phenomena (Lawton, 1995; Janssen, 1998; Bailey, Bras & Allen, 1999).

During the last decade or so, attempts have been made to expand the thermodynamic paradigm of life, particularly in the search for the underlying principles of ecology (Schneider & Kay, 1994; Toussaint & Schneider, 1998). Schneider and Kay (1994) argue that the Second Law is not only a necessity when describing living and meta-living processes, but also provide principles determining causality – the developmental process, guided by attractors in the system's potential landscape. The physical and/or chemical gradients created by energy/matter fluxes in open systems, and the resulting metabolic behaviour, are the central points of focus.

The researchers proposed a 'redefinition' of the Second Law, capturing these essential developmental properties. The following points can be made: Firstly, thermodynamic systems in equilibrium resist being moved away from their equilibrium state. The second point, is that when gradients are applied that push the system from equilibrium, the system, in trying to reach its local equilibrium attractor, will attempt, using all available avenues, to minimise the field potential or reduce/degrade the gradient. Thirdly, the effect of the system's local equilibrium attractor increases as the applied gradient increases. The fourth point is that other attractors may emerge in which the system may organise to degrade the gradient. And finally, conditions permitting (i.e. kinetic and/or dynamic), self-organisation may occur - indeed is expected to occur.

Thus, dissipative structures do not only dissipate matter and energy, as first emphasised, but also dissipate gradients and may emerge wherever applied. Living and meta-living systems evolve and develop solely in response to gradients caused by the incoming solar energy. Gradient dissipation occurs through degrading the exergy content of the total incoming solar energy. The entropy exported from the system is in the form of heat energy. Schneider and Kay (1994: 633) state that:

> 'This is the overall thermodynamic direction of evolution . . . to dissipate and degrade the energy flowing into the system. The cornerstone of our theory is to view living systems as the solution to the thermodynamic problem of increasing the degradation of the incoming solar energy, while surviving in a changing and sometimes unpredictable environment'.

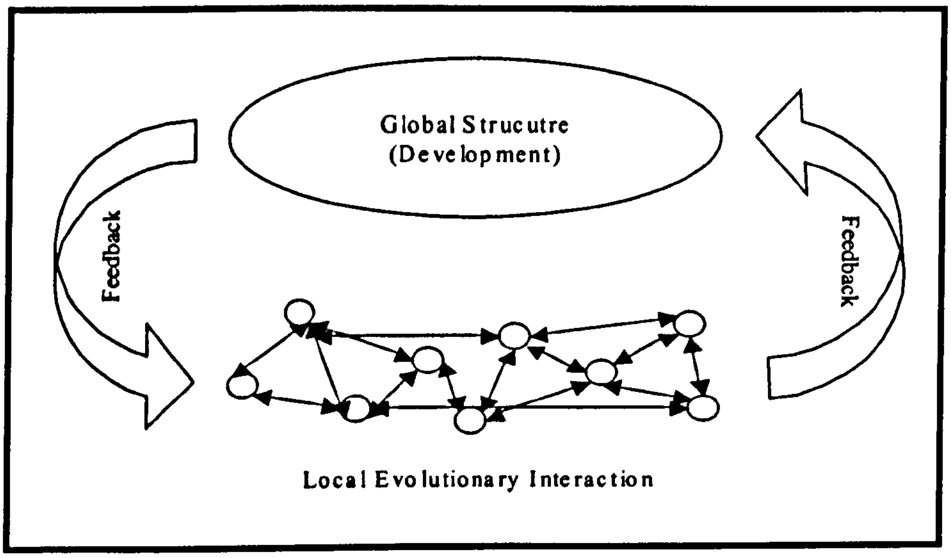
The above problem is solved with the development of systems (Nicolis & Prigogine, 1977; Wicken, 1978; 1979; 1980; Nicolis & Prigogine, 1989), seen as chemical factories, which further form a 'super-system' at the next level of aggregation. Gradient degradation is seen as transforming the solar energy's exergy content into chemical bond (stored) and heat energy. Gradient degradation increases through diversification in both the materials to be metabolised and, in turn, the agents of metabolism (the chemical factories). To degrade the exergy content, the super-system develops two pathways. One develops to produce and build complex molecular structures (grazing pathway), the other pathway breaks down these structures (detrital pathway). These pathways are of course extreme cases and largely artificial, in reality species may lie anywhere between the two extremes.

In the grazing pathway there would first of all have to be primary producers, species that directly tap into the incoming energy, that is the photosynthesisers. More systems may emerge to tap into this indirect source of the incoming energy – the grazers. These, of course, lead to trophic levels witnessed in ecological systems – systems feeding on other systems' potential energy, and so on. The pool of building blocks available to the primary producers, in a world of finite resources would soon be depleted as time goes on. This is where the niches for the species of the detrital chain open up. Species dedicated to detritus are essentially the matter simplifiers – they extract the remaining potential energy and useful materials to fuel and maintain their structures but in doing so provide the building blocks for the primary producers. The interactions and interconnections are more in the form of webs - complex food webs offering many and diverse energetic and metabolic flows.

One important additional assumption the N-ET model makes concerns the notion of attractors in systemic development. Langton (cited in Lewin, 1999) depicts this process well (see figure 4.1). The local interactions between the sub-systemic units result in an emergent global structure, which constitutes the attractor in systemic development. This in turn influences, through selection, the evolutionary processes (trial and error) of the sub-systemic units, which in turn feedback and influence systemic development. In the words of Langton (cited in Lewin, 1999: 189):

> 'both directions are important, linked in a tight, never-ending feedback loop. The whole system represents a dynamical pattern, with energy being dissipated through it . . . There's nothing driving the system; the dynamics come from within the system itself.'

Figure 4.1. Development and evolution (adapted from Langton and cited in Lewin, 1999)



4.3. Natural Systemic Development

Lovelock's work (Margulis & Lovelock, 1974; Lovelock, 1989a; 1989b), also drawing from Schrödinger, and Prigogine and colleagues, is perhaps the most ambitious attempt to describe a coherent meta-biological system (see also Sagan &

Margulis, 1983; Brown, Margulis, Ibarra & Siqueiros, 1985; Craik, 1989; Kirchner, 1989; Baerlocher, 1990; Gorham, 1991; Barlow & Volk, 1992; Levine, 1993; Tickell, 1993; Lenton, 1998; Huggett, 1999; Wilkinson, 1999a; 1999b; Downing & Zvirinsky, 2000). Gaia Theory has been stated, as an 'entity involving the earth's atmosphere, biosphere, oceans and soil' (Margulis & Lovelock, 1974: 473) with 'regulation, at a state fit for life . . . a property of the whole evolving system' (Lovelock, 1989a: 144).

In response to criticisms of teleology (e.g. Dawkins, 1986; 1989), Lovelock developed a mathematical model called 'Daisyworld' which demonstrated through simple rules how a planetary metabolic phenomenon has evolved with global emergent properties. In terms of earth this is manifest in the homeorhesis of climate and chemical composition, which, through the modulating effect of the whole evolving system and the feedback processes constituting the totality, self-regulates an optimal physical and chemical environment for an indefinite persistence or sustainability (Lovelock, 1979; 1985; 1988; 1990). This extends and confirms Schneider and Kay's (1994) basic assumptions that living and meta-living systems are subject to and can be described by non-equilibrium thermodynamic principles inherent in the non-linear dynamics of open systems.

Two characteristics inherent in evolutionary complex systems, of a physical nature are metabolism, i.e. the distribution of materials, energy and information flows (Erkman, 1997) and development or adaptive self-organisation (Kauffman, 1995). Odum (1969; 1971; 1997b - and industrial ecology in general) argues that the development of natural systems and associated shifts in metabolic activities, or ecological succession, has many parallels with the socio-industrial development of human society (Odum, 1969; 1971).

This chapter argues that the similarities between natural ecology and industrial ecology are more intimate, homology rather than analogy. The synthesis of non-equilibrium dynamics, with biology and ecology (and industrial processes), is related to the properties of energy and matter in particular states and conditions. Systems, open to the flux of energy and matter, in certain non-equilibrium conditions, create gradients and sometimes give rise to the emergence of metabolic behaviour.

Consistent with this, Odum (1969; 1971) defines ecosystem development in terms of three parameters:

1. An orderly and directional process of developmental biological organisation
2. The co-evolution of biota and abiota, each defining, moderating and limiting the other
3. And, the climax towards system stability.

The general trends, identified by Odum (1969), in the developmental and evolutionary changes in the functional properties of natural systems, however, do not explain the underlying processes. In an attempt to rectify this, Loreau (1998) proposed a model of competition within- and between-materials cycles. This thinking may have an important role in explaining the problems now associated with the metals manufacturing system in Sheffield and South Yorkshire. Loreau (1998) argues that material cycling, or more specifically the ensuing competition within- and between-materials cycles, strongly influences the organisational characteristics of ecosystems. Within-cycle competition is described as the competition between organisms in spatially homogeneous material cycles, and is argued that this increasingly favours organisms with greater resource use intensity. The between-cycle competition occurs between organisms in spatially heterogeneous cycles, and is argued that this increasingly favours organisms with traits that act to lessen nutrient leakage.

It is interesting to reconcile Loreau (1998) with Schneider and Kay (1994: 634), who argue that:

> 'The characteristic of these chains is that they would degrade as much of the incoming solar energy as possible per unit production of complex molecules.'

Therefore, not only does the selection pressure from within- and between-materials cycling favour organisms with increasing resource-use intensity and systemic retention of nutrients but also those with the most efficient processes, in terms of energy usage. The history of the material cycle is then thus: in the early stages, available materials are typically metabolised by organisms that are wasteful (in a systemic sense) of both matter and energy. As the system matures and matter and energy become increasingly limited, selection pressures favour those organisms with a more efficient and conservative utilisation of available energy and materials.

Thus to recap, the synthesis of non-equilibrium thermodynamics, with biology, ecology and the industrial process, comes down to the properties of energy and matter in particular states and conditions. Systems, open to the flux of energy and matter, in certain non-equilibrium conditions, create gradients and may give rise to the emergence of metabolic behaviour. Open systems, in attempting to degrade the impinging energy gradients, utilise the available matter and metabolise it. In doing so, the self-organisation of ordered process structures occurs, gradients are degraded, entropy produced and exported increasingly faster, and the Universal trend towards heat death is increased as required by the Second Law. The N-ET model assumes that systems with a physical metabolism exhibit patterns, therefore eliciting predictions, not only in structure, function and organisation but also in evolution and development. This is the basis for the argument of homology.

4.4. N-ET Model of Industrial Development: Hypotheses and Results

The proposed model of industrial development applied to metals manufacturing was developed to meet several goals. First and foremost, it aims to support and build on both the concept of IE and Schneider and Kay's (1994) non-equilibrium thermodynamic paradigm of life by focusing on homologous, rather than analogous, processes underlying both natural and industrial systems. The N-ET model also attempts to both incorporate the findings and important aspects that were unearthed in the review of South Yorkshire's industrial history at the beginning of this chapter, and develop the work of several other researchers (e.g. Templet, 1996; Wallner, Narodoslawsky & Moser, 1996; Templet, 1999; Wallner, 1999; Korhonen, 2001). This is achieved by incorporating other phenomenological attributes proposed in the literature of natural ecology. On building on the non-equilibrium thermodynamic rationale presented in the last section, a detailed comparison is needed between the observations made in both natural and industrial ecosystems. Odum (1969; 1971) focuses on five main groups of phenomenological attributes, which for the purpose of this model will be adapted and presented as hypotheses for both natural and industrial systems. These are:

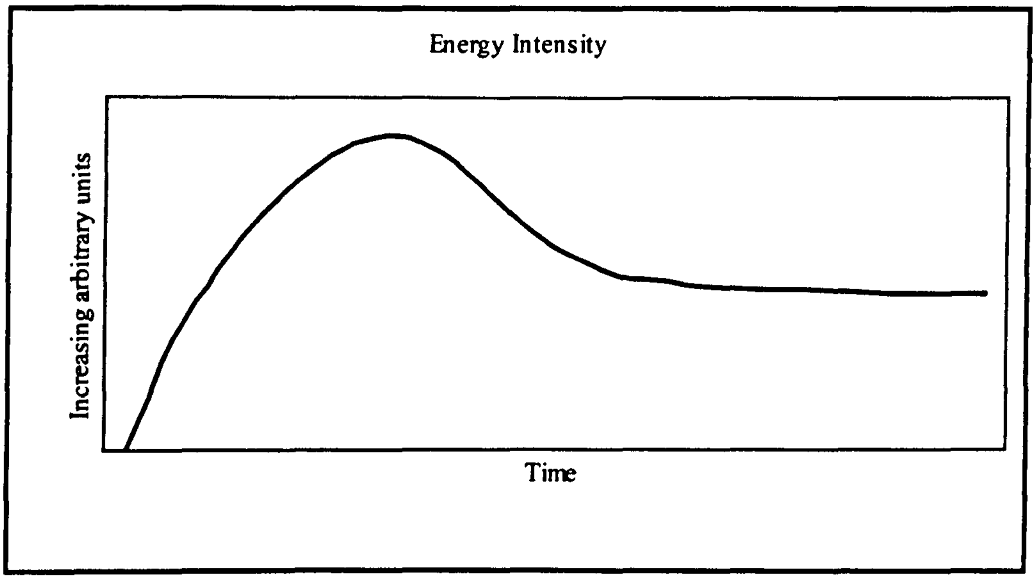
1. **The closed-loop hypothesis**: Closed-looping behaviour is a strong attractor in the industrial system's potential landscape, thus a natural tendency
2. **The energy hypothesis**: Patterns in industrial energy intensity will be homologous to patterns in ecosystems, both in specific materials cycles and in a general systemic sense
3. **The diversification hypothesis**: Industrial diversification, particularly in developing systems, will be witnessed at several levels of aggregation: in metabolites, organisational forms (firms), in specific industrial processes (within-industry analysis), and in regional, national and global economies (between-industry analysis)
4. **The selection hypothesis**: Selection pressures begin to favour certain behaviours in individual firms and their organisational life histories begin to change becoming longer and more complex. Symbioses develop and then predominate – firms change from being self-oriented to system-oriented
5. **The punctuated systemic control hypothesis**: The net result of these highly interconnected and interdependent interactions is the emergence of overall system stability or homeostasis, where environmental perturbations are minimised.

The methodology consisted of data collection from existing literature sources and historical records. Although South Yorkshire is the specific case study, certain data sources were either incomplete or absent. Therefore, data representative of the South Yorkshire situation, metals manufacturing areas, or from national and international databanks from which general trends could be identified, were also used. The results presented in the following sections are based purely on observations and data collected firstly in ecological and then industrial systems with the aim of comparing and analysing patterns in both systems.

4.4.1. Energy Intensities

It has been observed that natural successional energetics appear to follow specific trends and apply to forest ecosystems, laboratory microcosms, large water ecosystems and seasonal successions (Odum, 1969 - see figure 4.2). Four main phases can be elicited. Energy intensity increases rapidly in early development, peaks, begins to decline and then plateaus.

Figure 4.2. Successional energetics in natural systems (adapted from Odum, 1969)



The same patterns in energy intensity, as the N-ET model hypothesises, may also be found in global and national economic systems[1]. Grübler (1994) argues that global industrial output has increased a hundred-fold since the industrial revolution and forty-fold in the last 100-years – a 3.5% annual growth rate. In the same period, labour productivity, i.e. energy efficiency, has increased by a factor of 200. Grübler (1994) also observes that in the early phases of industrialisation, energy intensities rise dramatically, whereas industrialised countries are characterised by ongoing declines. Similarly, Templet's (1996; 1999) evidence also indicates a transition in energy patterns in industrial development. He states (Templet, 1996: 13):

> 'An observed energy transition is characterised by low energy efficiency as a country first develops, followed by increasing efficiency as the transition is passed. Energy intensity, the energy required to generate a unit of output, is an inverse measure of efficiency and reaches a peak at

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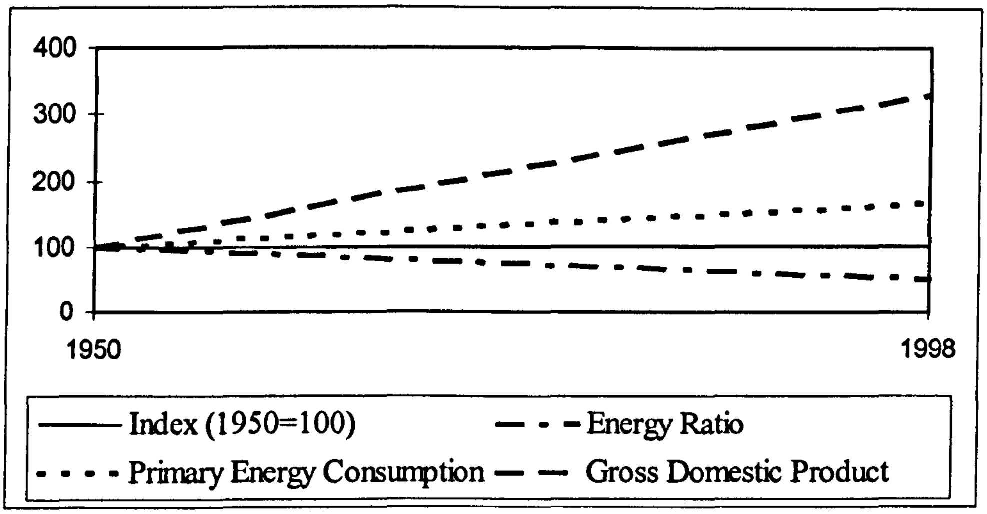
[1] The model assumes that energy in industrial systems is present in several forms, for example, normal energy (fossil fuels, nuclear, biomass), manual labour and money/capital e.g. Spreng, D. T. (1984). On the entropy of economic systems. From Microscopic to Macroscopic Order. Frehland, E., Ed. Berlin: Springer: 207-217..

> the transition. Below the transition, countries increase energy use faster than GNP so energy intensity rises rapidly along with material use and pollution while socio-economic indicators improve. Beyond the transition, however, environmental and economic indicators improve only as energy intensity declines.'

During 1950 and 1998 gross domestic product (GDP) of the UK economy increased by over 200% while primary energy consumption increased by 60% (levelling out between 1970-1998). The energy ratio (GDP/primary energy consumption), therefore, actually decreased by 50%, i.e. 50% more efficient (see figure 4.3). Of the total energy consumption of the UK, industrial processes account for 22%. It is interesting to note the energy efficiency, based on energy consumption/output ratio between 1970 and 1998, increased by approximately 60% (DETR, 1999b). From this it could be argued that the energy intensity of the UK's economy, as it is a largely mature economy, has long since peaked and is now in decline but still far from the plateau phase.

Figure 4.3. Energy efficiency of the UK economy[2] (adapted from DETR, 1999b)



The energy hypothesis also applies to specific metabolites. With steel, Szekely (1996) notes that in the last 25-30 years both the labour to produce a ton of steel has decreased from around 12 to 0.5 man-hours, as well as a 40% reduction in the amount

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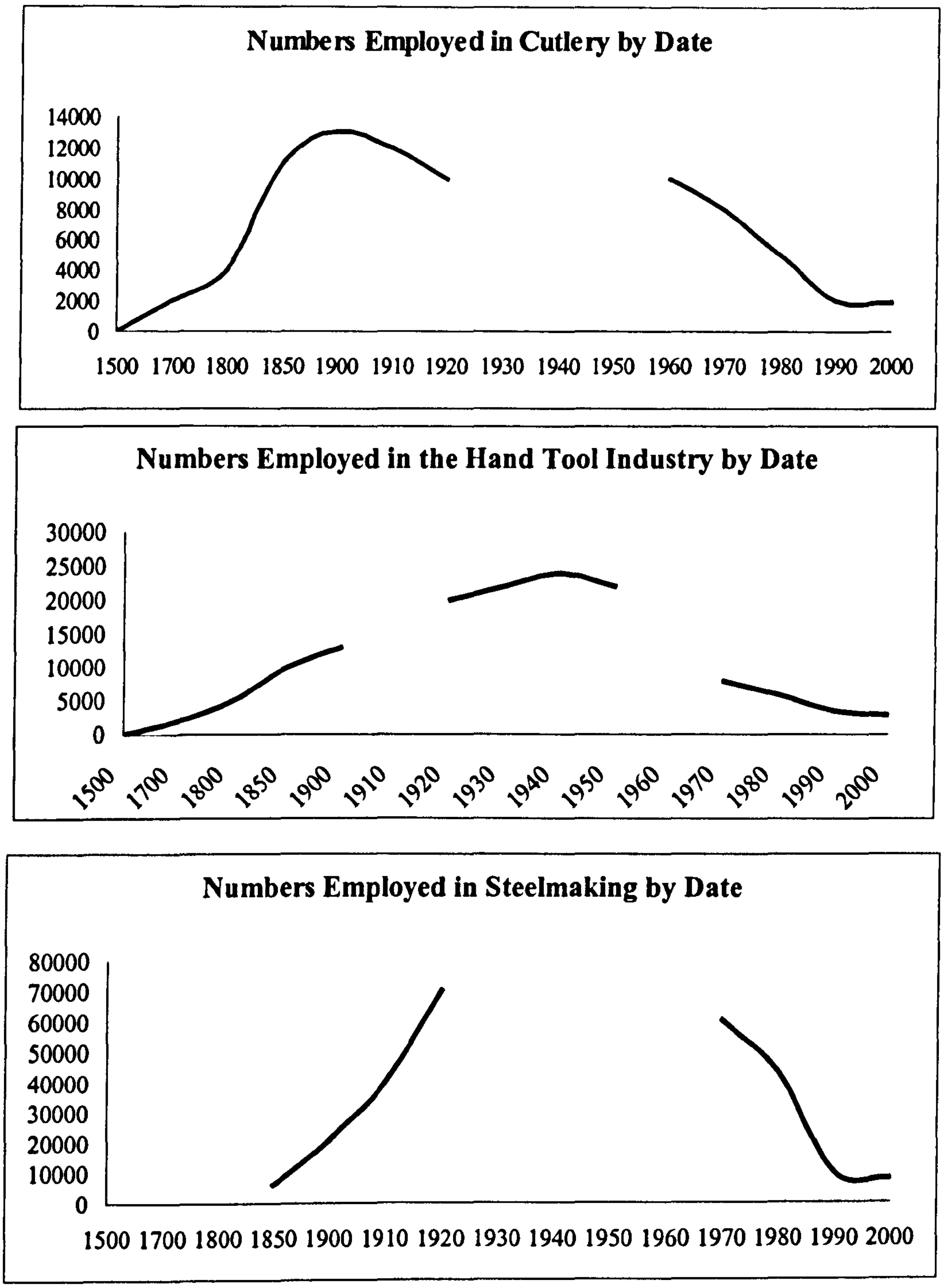
[2] Note that figure 6.3 is intended to demonstrate the change between the indicated dates only. Although there is some variation the general trends are the same.

of normal energy. This is arguably all through innovation driven by intense competition created by the increasing market globalisation. No data could be found for the early energy intensity of the metabolising system. Thus, it would be fair to say that at present the system appears to be between the final two phases (i.e. the decline and plateau phases).

The review of South Yorkshire's industrial history also described the similar rise and falls in employment in the cutlery, hand-tool and steel industries. Employment in cutlery in 1679 stood at 2,000 and by 1800 it was 4,000. During 1850 and 1960, employments fluctuated between 10-13,000. In 1970, decline was evident with the employment figure at 8,000. By 1980 the figure was 5,000, in 1994 it was 2,000 and the decline is predicted to continue. The early trends of employment in the hand-tool sector reflected cutlery's trend and reached 11,000 by 1850. In contrast, however, employment more than doubled cutlery's figure in 1935 and stood at 24,000. Nonetheless, employment decline also occurred and reached 8,000 by 1971. In 1989, employment stood at 3,650. The steel industry faired no better. In 1850, the employment rate was 5,000. By 1911, it soared to 40,000. Employment reached its highest level in 1971 with 60,000 strong workforce. However, just over two decades later (in 1994) the workforce shrank to less than 10,000. As can be seen in figure 4.4 with the decline in employment in the metals' industries, the implications of this trend directly relate to the recent systemic decline in South Yorkshire. What is striking, however, is the similarity in patterns between natural energy trends and employment trends (i.e. when comparing figure 4.2 with figure 4.4).

Figure 4.4. Employment trends in Sheffield's traditional industries (Tweedale, 1995)



There are, however, a couple of caveats when dealing with the energy intensities hypothesis overall. The first concerns the quality of the data particularly in the early stages of development. In both the global and national economies as well as the specific metabolites, in this particular case metal, data is either missing or far from complete. Furthermore, data for the national economy is for a mix of industrial sectors, some mature and some in their early stages of development which also presents a problem. Further research is needed to untangle the data for both the mature and immature sectors. Even the employment records for the steel industry have periods where data are absent. One other problem with the employment data is that declines in employment may also be due to the metals manufacturing system being global in scale with variations between regions. Nonetheless the general trend can still be elicited (see figure 4.4).

One further criticism is that humans have much more of an influence now than in the past particularly over the time periods involved in the energy intensities trend. This is exemplified by the communications industries and dot-coms, whose values soured and then declined quite rapidly in a timescale involving months and years rather than the decades and centuries involved in the older industries. Human influences and attributes such as culture, confidence, and perceptions are beginning to take much more of a role in the contemporary development of industrial systems, particularly in stock speculation. The increasing ease and rapidity of communications is also playing a significant role in industrial development in both decision-making and the consequent action, and material transportation. The same can be said of the impact of religion, trade-unionism and community spirit highlighted in the review of Sheffield's industrial history. The community spirit and religion had significant influences on the early development of South Yorkshire's industries and played a key role in innovation. Trade-unionism, although having positive impacts (e.g. in pay, housing and education) it also had a very negative impact when the time came to re-organise and modernise. The quality over quantity argument, which had contrasting impacts on cutlery and hand-tools (and tool steels), is also another example of the unpredictability and uncertainty of outcomes that human influences have.

However, there is still good evidence that the *underlying* patterns in energy intensities, nonetheless, still follow the same trends. Thus, patterns in global, national and regional industrial economies as well as patterns in specific metabolisms, such as the steel metabolism, support, with some qualifications made, the energy intensities hypothesis in that homologous to ecological systems, industrial trends in energy intensities, rapidly increase, peak, decline and then plateau.

4.4.2. Production and Recycling

In pioneering natural ecosystems, primary production typically exceeds community respiration, as space and resources are plentiful and constraints minimal. Net system production is high and structures and organisations accumulate steadily increasing biomass throughout. With growth, however, space and resources inevitably become limited and begin making an impact (Washida, 1995). The system then develops or self-organises towards maturity, through both perturbations and the ordering processes of natural selection (competition and co-operation) and the production to maintenance ratio approaches 1. The emphasis on growth or quantity shifts towards development or quality (Odum, 1969; 1971). This is associated with a number of other characteristic changes. One particular change is the increasing emphasis on cycling. Metabolic activities change from being linear to more web-like. Metabolites shift from being externally to internally extracted and exchange rates between system and environment slow. As such, the processing activities of the metabolic agents begin to close, and operate cyclically. This results in the collective conservation of metabolites. In a physical sense, maturity is towards systemic self-regulation (Odum, 1969; 1971). This category of phenomenological attributes constitutes much of the work within the discipline of industrial ecology/metabolism.

From the review of South Yorkshire's industrial history, it was evident that the local physical resources played a significant role in the region's early success. This is also consistent with Korhonen's (2001) locality principle. South Yorkshire's surrounding landscape played a very significant role in the region's early growth in terms of the resources that were readily available, such as water, coal, wood, sandstone, ganister, clay and silica. However, two other factors were also significant, which run counter to the locality principle, and involve the special agreements and monopoly over the supply of Swedish iron, and well as the rapidly increasing importance of the American market.

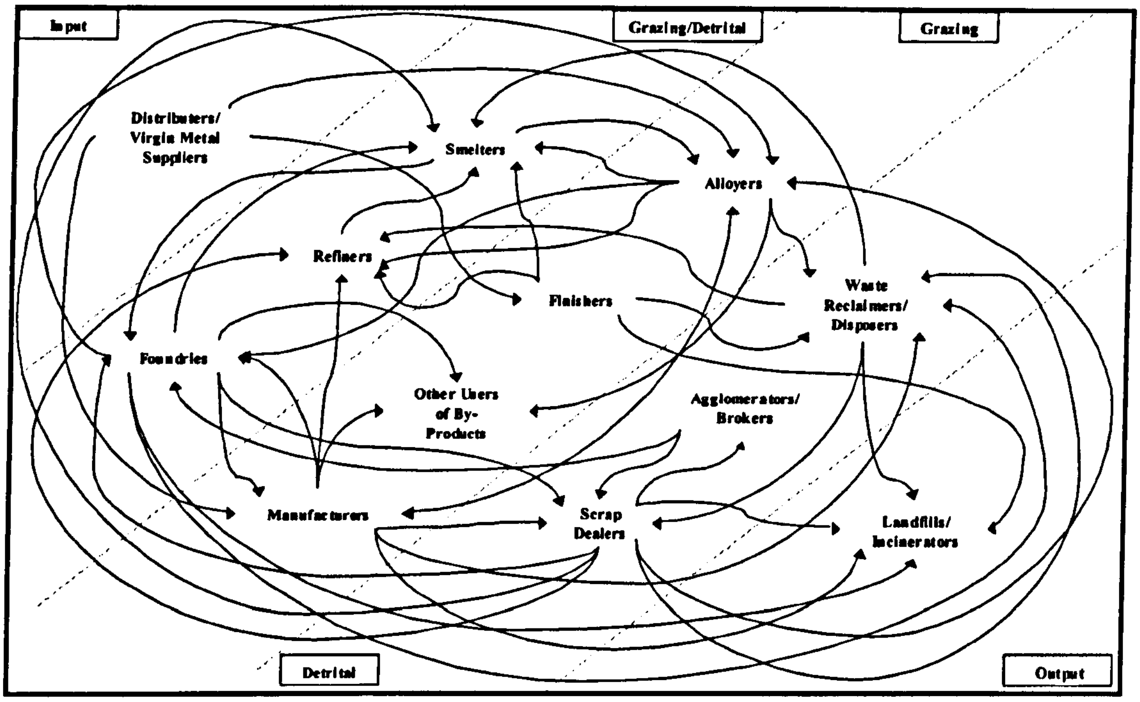
In terms of production, the above employment trends in Sheffield steel give a good indication of the sudden early rise in productivity. In addition to this, one good example of the South Yorkshire region's rapid expansion can be seen in the beginning of the crucible steel industry (see Tweedale, 1995). The crucible process was developed in the 1740s. By 1787 there were ten steel producers, by 1817 there were thirty-four and by 1856 there were more than a hundred. During a twenty-year period, between 1840 and 1860, the number of melting holes almost doubled from 1,333 to 2,437, resulting in a quadrupling of output, from 20,000 tons to 80,000 tons. The iron, stainless steel and other special steel industries also reflected this pattern (Tweedale, 1995). Early employment rates also reflect the degree of productivity. As demand was more or less satisfied, productivity and the number of producers levelled out and supported 'respiration'.

In terms of recycling, one of the main sources of inspiration behind the N-ET model was Sagar and Frosch's (1997) presentation of the natural closed-looping behaviour of the metals manufacturing system (see figure 4.5). Although the system described concerns the Massachusetts' regional metals system it also almost perfectly reflects activity in South Yorkshire. They argue that the main driving force behind the closed-looping phenomenon is purely economics. In their words they found (Sagar & Frosch, 1997: 44):

> 'that the factors underlying decisions taken by firms regarding metal flows are predominated by economics (to stay in business and maximise profits), regulatory concerns (to allow them to continue operations), and liability considerations (to prevent future economic costs).'

It is worth noting that the regulatory concerns and liability considerations that they emphasise are arguably fundamentally economic in origin. More of this model and how it evolved is discussed in the *diversification* section below.

Figure 4.5. Metals manufacturing system: Natural closed-looping (adapted Sagar & Frosch, 1997)



Interestingly, the N-ET model would predict, that as the system develops further, there would be no need to regulate and penalize. Supply and demand, through selection pressures, ultimately shapes metabolic behaviour. As virgin ore becomes scarcer, other sources become more attractive, particularly sources that were once sinks. Much of this infrastructure arguably developed prior to environmental regulation, being shaped purely by economic incentives through supply, demand and increasingly scarcer virgin ore.

This is further demonstrated by rare materials, such as those found in the silver, gold and platinum metabolisms. Also in support of the gradient degrading nature of the circular metabolism are the now famous Kalundborg industrial symbiosis park in Denmark and the Styrian system in Austria, both of which developed primarily out of economic considerations (Sagar & Frosch, 1997; Schwarz & Steininger, 1997).

However, when mapping these metabolic behaviours onto other metabolites, such as energy, wood, 'natural' resins, and textiles, problems begin to arise. Fossil fuels, for example, are completely degraded and irreversibly transformed at the endpoint, whereas renewable metabolites have the potential for new inputs as new crops are harvested.

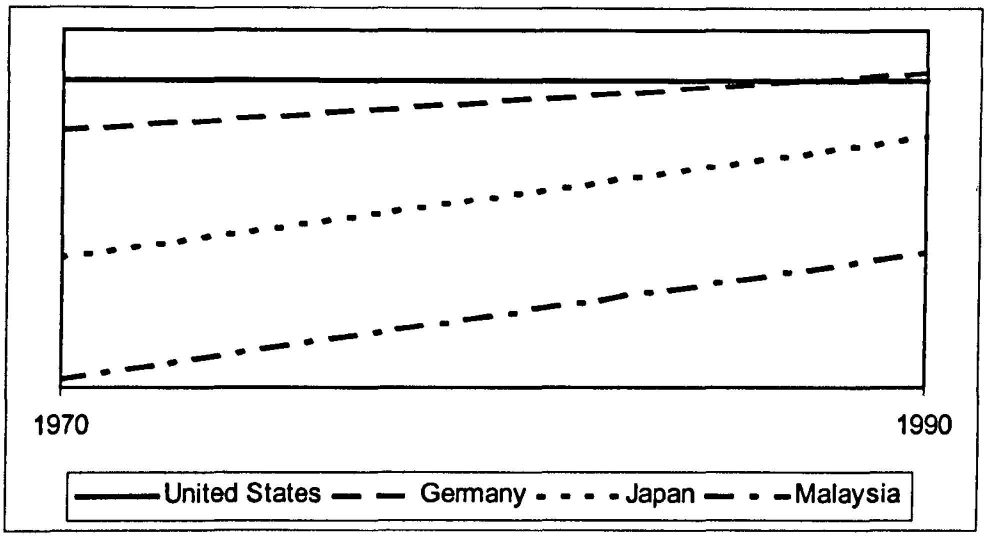
What distinguishes metabolisms involving metabolites such as metal is that they are absolutely non-renewable and have a finite resource base much like the nutrients in closed natural systems. With this qualification in mind, we can conclude that, when comparing natural and industrial systems, in this case metals manufacturing, there appears to be the same patterns and processes involved in production and recycling that suggest homology. It is, however, worth investigating the extent to which the activities of renewable materials as well as irreversibly transformed materials resemble natural systems and to determine if the underlying processes in these metabolisms are also homologous.

4.4.3. Diversification

The diversification process in natural ecosystems is directly linked to both the patterns in energy intensities and production and recycling (Huston, 1979). With diversification, the system composition becomes more varied, both individual organisations/number and individual organisations/area ratios increase. In addition, the apportionment of individuals between organisations evens out, i.e. equitability increases. Metabolites also diversify (Odum, 1969; 1971).

Templet (1999) found, working from the Shannon-Weaver formula (Shannon & Weaver, 1949), that economic diversity, measured by the number of sectors as well as the equitability of energy through them, generally increases through time. Templet (1999) argues that diversity is a good general indicator of economic development. Figure 4.6 shows graphically some of the findings – diversification trends between 1970 and 1990 in Germany, Japan, Malaysia, and the US. As one would expect, the economies of the US and Germany, being two of the first nations to industrialise are far more diverse than, for example, the newly developing Malaysian economy.

Figure 4.6. Diversification by country through time (adapted from Templet, 1999)



The diversification hypothesis also applies to regional economies, specific industrial processes and the level of the firm. Sagar and Frosch's (1997) model is also applicable here (see figure 4.5). In early development, the structure and organisation of this system consisted of a purely linear process, typically, virgin ore extractors through to the smelters and manufacturers through to landfills. As both processes became more sophisticated and productivity increased, through innovation and mutation, niches for refiners, foundries, finishers and alloyers begin to open up. The interesting part is where it becomes more economical to reuse manufactured items rather than virgin ore as natural stocks decline. This results in the niches in the detrital cycle opening up. Firms involved in waste reclaimers, scrap dealers, dismantlers, agglomerators and other users of by products represent these niches. With maturity this system is highly interdependent and interconnected and thus has an increased equitability.

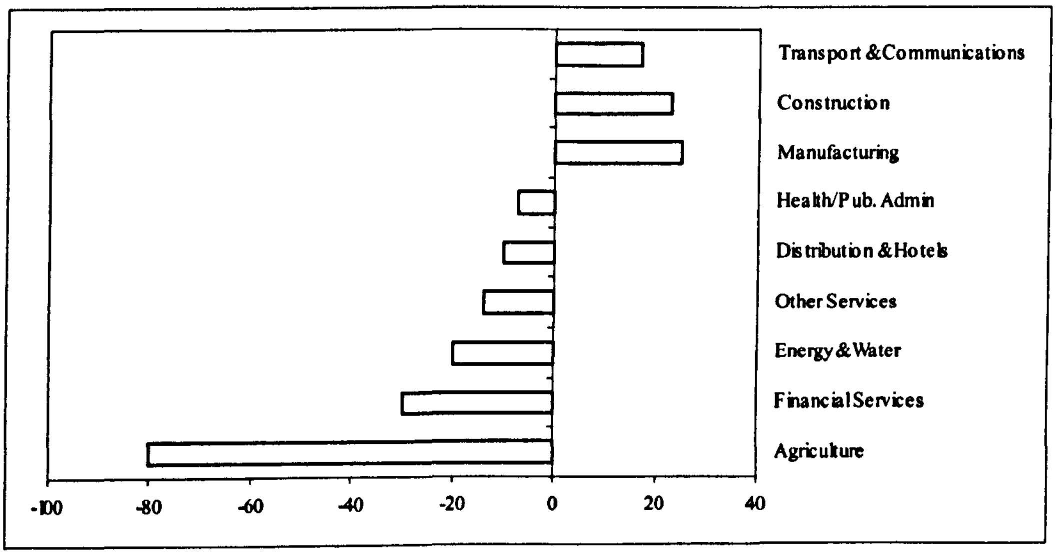
Support for the hypothesis may also be found in the South Yorkshire's industrial history. Take, for example, the rapid diversification processes involved in the cutlery's and hand-tool's allied trades. As early as 1824, there were over sixty supporting industries. For example, there were firms specialising in acid etching, pearl, ivory, horn, glass, gold silver and paper (for packaging) as well as organisations dealing with clay, charcoal, coke, ganister, iron, plate and silica. Table 4.2 demonstrates the diversity among the trades associated with hand-tools in 1871.

Table 4.2. 1871: The hand-tool manufacturers in Sheffield.

No. in Sheffield	*Type*	*No. in Sheffield*	*Type*
19	Anvils & vices	42	Hay & manure forks
24	Augers & gimlets	56	Joiners' tools
20	Awl blades, steel tacks & needles	2	Mill chisels
10	Bookbinders' tools	3	Plasterers' tools
10	Brace & bits	5	Rules (box and ivory)
78	Edge tools	104	Saws
49	Engineers' tools	27	Scythe & sickle
7	Engravers' & carvers' tools	20	Sheep shears
171	Files	6	Silver- & coppersmiths' & tinners' tools
11	Garden shears	11	Spade & shovel
11	Garden tools	3	Strickles
39	Hammers	6	Weavers' shears & nippers

Although these patterns are characteristic of the metals manufacturing systems in South Yorkshire, that is, the industry concerned with metals is highly diverse, the present socio-economic problems, as a regional system, are arguably directly related to *lack* of diversity at the next level of aggregation. As can be seen in figure 4.7, compared to the UK average, the local economy over-relies on manufacturing, construction and transportation. In other words, there is a serious under-representation of services, leisure and recreation, business services, distribution, retail, hotels and restaurants, and public administration, education and health.

Figure 4.7. Industrial structure in South Yorkshire (adapted from SFP, 1999b)



This also presents a problem for the N-ET model in which further research is needed to clarify issues. Concepts such as 'lock-in' and path-dependency in the complexity literature (e.g. Holland, 1995; Allen, 1998a; Lewin, 1999) are particularly worth considering in this instance. In this context, perhaps the success of the metals industry stunted growth in other non-related areas.

The starting point for all aggregate trends in diversification are entrepreneurs and their organisations. Tweedale (1995: 14), in a comprehensive socio-economic history of Sheffield, illustrates the diversification process in metabolites, the various uses of tool steel, and the outcome of such processes:

> 'The use of tool steel – defined simply, they are the steels which enable other materials to be formed, shaped, or cut – are wide ranging. There are shapes and sections which can best be produced by hot extrusion, calling for hot-die steels which can withstand high temperature, high stress, and abrasion. Hot and cold sawing and shearing, drop-stamping, cold-rolling, cold-heading, deep-drawing and many similar cutting and machining operations each demand a different type of tool steel. Carbon tool steels, the oldest of the special steels are used for wood tools, shear blades, burnishing rolls, cams, mandrals, rock drill pistons, and dies of many types. There are also steels which have been developed for pressure-die castings, extrusion, plastic moulding, and hot-working and maraging steels. For cutting steel itself, complex high speed steels have been developed for use in twist drills, reamers, hobs, and in tools for turning, milling and shaping.'

Before concluding this section, there is a potential dichotomy relating to the diversification process and stability issues at both microscopic and macroscopic levels. However, these issues are more directly concerned with the homeostasis hypothesis and will be discussed in section 4.4.5. Therefore to conclude on the diversification hypothesis, trends at the levels of the global, national and regional economies, as well as patterns at the level of the firm and specific industrial processes, give sufficient support to the hypothesis. That is, diversification trends in natural and anthropogenic systems are enabled and limited by homologous processes.

4.4.4. Organisational Life Histories and Selection Pressures

With natural ecosystem maturation, strong processes of negative and positive feedback emerge, i.e. internal symbioses develop e.g. mutualism, parasitism, predation (in a systemic sense, i.e. overall efficiency), and commensalisms. As these feedback control mechanisms develop, selection pressures alter and the life histories of individual units/organisations' begin to change (Donald, 1958; Newman, 1973; Wilbur, Tinkle & Collins, 1974; Demetrius, 1977; Southwood, 1977; Pickett, 1980; Leps, Osbornova-Kosinova & Rejmanek, 1982; Odum & Biever, 1984; Burns, 1994; Wu & Loucks, 1995; Mageau, Costanza & Ulanowicz, 1998). Niche specialisation increases in line with both the development of the detrital pathway and diversification (Grubb, 1977). Life cycles of the species change from being short and simple to being longer and more complex, whilst growth form changes from '*r*-selection' (rapid growth) or self-oriented to '*K*-selection' (feedback control) or system oriented (Odum, 1969; 1971; 1972; Putman & Wratten, 1984).

The network paradigm introduced by Cooke and Morgan (1993) is directly related to the emerging developmental change in selection pressures and the organisational life histories of the individual firms (see also Foray, 1990; Bramanti & Senn, 1991; Camagni, 1991; Freeman, 1991; Gordon, 1991; Kamann & Strijker, 1991; Ratti, 1991; Verheul, 1999). Some oft quoted examples of networks and clusters include Silicon Valley (Saxenian, 1991), Prato (Gillies, 2000) and Baden-Württemberg (Cooke & Morgan, 1993). The key characteristics of this emerging form of development, corporate and spatial, are, in the words of Cooke and Morgan (1993: 562):

> 'interdivisional integration, total quality, delayering, user involvement, market response, alliances, and collaborative subcontracting. There is a strong thread running through these principles which stress cooperation, collaboration, and the maximisation of collective competences.'

Similarly, Powell (1990: 78), in distinguishing networks from markets and hierarchies, states:

> 'in network modes of resource allocation, transactions occur . . . through networks of individuals or institutions engaged in reciprocal, preferential, mutually supportive actions . . . that parties are mutually dependent upon resources controlled by another, and that there are gains to be had by the pooling of resources . . . individual units exist not by themselves, but in relation to other units . . . Benefits and burdens come to be shared . . . Complementarity and accommodation are the cornerstones of successful production networks.'

Interestingly, Wallner (1999) argues that the individual enterprises, without relinquishing their autonomy, self-determination and self-responsibility, are subservient in that their functions not only benefit themselves but also the networking system (see also Axelrod & Hamilton, 1981).

There are also specific examples from the review of South Yorkshire. In particular, the network and clustering phenomenon that was thought to play a critical role in the region's success. The outwork system is one example as can be seen from this quote by an overseas visitor to a local razor works, writing in the Sheffield Independent, on the 5th December 1868, supports this view of the industrial structure (cited in Tweedale, 1995: 47):

> 'We found the workmen not altogether in one factory, but in different buildings. In one was where the rough process of forging was performed; from thence, perhaps across a street, the blades received further touches from other workmen, and so on till . . . they were carried to the grinding and polishing works, some distance off, and finally returned to a building near the warerooms, to be joined to the handles, after which they were papered and packed, immediately adjoining the warerooms proper, where sales were made and goods delivered.'

In its early history, Sheffield steel as a system gained and sustained its competitive advantage for decades if not centuries mainly through its clustering of activity. Every firm, and every working person, was in some way connected and enveloped in the threads of industrial communication and information. The process of innovation, arguably a property of both the intense clustering of the industry and the ease of entry into the trades, is a very interesting phenomenon. Sheffield's success came from the bottom up. The intense clustering and the extensive networks established (encompassing local financiers and banks), gave the ordinary worker the opportunity to enter and prosper in either the cutlery, hand-tools, or crucible industries, with relatively little risk (Lloyd-Jones et al, 1994). The dense networking appears evident not only within particular trades, but also between trades, particularly the related and supporting industries. The result being a highly interconnected and interdependent and yet vastly diverse regional manufacturing system (Keeble, 1997) With the cutlery, hand-tool, and the steel industry structured in this way, innovation, entrepreneurship and adaptability was the norm. Cutlers, prior to mechanisation and the standardisation, prided themselves on adaptability and filling specialised niches.

However, it is important to distinguish between what researchers think is happening or what they would like to happen and what *actually is* happening. Although co-operation, collaboration and inter-disciplinarity (in academia) are the current buzzwords, they are besieged with problems. Confidence and trust between parties is paramount and breaches, particularly in industry, are probably an ever-present problem. Sheffield's most famous trade, the cutlery industry, with its secrecy, overriding obsession with trademarks and an unwillingness to change (Tweedale, 1995), dramatically demonstrates these problems, through its demise.

Thus, with the above caveat, patterns in organisation and structure both within- and between-firms, such as trust, co-operation, collaboration and other symbiotic relationships (organisational life histories), as well as changes in selection pressures (from *r*-selection/self-oriented to *K*-selection/system-oriented) provide tentative support in that they appear to involve rules and processes homologous to natural systems. However, more research is required and is now being conducted particularly concerning issues of trust and confidence, and to untangle prescription from reality.

4.4.5. Homeostasis, Sustainability and/or Punctuated Systemic Control

The net result of the above phenomenological trends in natural systems is a climax towards system stability, collective/systemic control or homeostasis (Odum, 1969; 1971). However, the notion of climax, in that there emerges systemic stability or homeostasis, is the most problematic for interpretation. One problem is that the concept of sustainable development has been taken as a synonym for the climax stage in natural ecosystems (Connell & Slatyer, 1977; Ulanowicz, 1980; Hawken, 1993; Christensen, 1995; Chapin, Torn & Tateno, 1996; Odum, 1997b; Ulanowicz & Abarca-Arenas, 1997). The N-ET model suggests that although a form of sustainability is strived for at the macroscopic level, there is inherent uncertainty at the microscopic level (Benci & Galleni, 1998). One other potential dichotomy concerns diversity. Greater diversity generally associates with greater stability and productivity at the systemic level. However, greater diversity is also associated with greater fluctuations (and uncertainty) at the sub-systemic levels, and vice versa (Moffat, 1996). In terms of the metabolism perspective nonetheless, sustainability, homeostasis and self-regulation are far easier to grasp. As can be seen in Sagar and Frosch's (1997) closed-looping behaviour, the actual metabolite achieves a sustainable process. The metabolisers, however, come and go in line with the energy, diversification and selection pressures hypotheses.

But another concept is needed to replace homeostasis, self-regulation and sustainability. 'Punctuated systemic control', with Gould and Eldridge's (1977; see also Gould, 1982; Gould, 1989) concept in mind, is perhaps a better descriptor. To elaborate, the central focus of evolution is metabolic behaviour. Once one metabolic system reaches exhaustion or its most effective closed-looped state, through the processes of natural selection, the metabolising sub-systems, building on the former metabolic system, evolve mechanisms to metabolise other material. This process continues until somewhat discreet but highly interconnected and interdependent ecosystems emerge. In terms of Schneider and Kay's (1994) theory, systemic development is in direct response to, and functions primarily to degrade, the impinging gradients created by solar radiation. Consistent with this is Langton's (cited in Lewin, 1999) notion that the local interaction and emergent global structure continuously feedback and thus continuously evolve and develop.

4.4.6. Model Conclusions

The N-ET model, the hypotheses, and the preliminary supporting evidence, is arguably a good model or framework within which industrial organisation, structure and function, as well as evolution and development, can be understood and represented. Furthermore, the model assumes that the drive towards sustainability is a natural process and given time and patience requires no active human intervention. Nonetheless, the macroscopic knowledge of systemic development can be utilised and some of the trial and error involved in microscopic evolution may be avoided. However, qualifications need to be made. First and foremost, the data presented has a very strong bias to the metals industry and may not apply to other metabolites such as energy, wood, textiles and other renewable materials. There is also a need for further more detailed research into each of the hypotheses to untangle the underlying natural, homologous processes and the human influence. These may include the influences of culture, human personality and drives, and even genetic and other information flows.

4.5. Discussion

The N-ET model raises several interesting points in terms of guidelines for policy and decision-makers concerned with South Yorkshire's socio-economic decline and subsequent regeneration. Firstly, the closed-loop hypothesis is perhaps the most reassuring of all hypotheses. As Frosch et al (1997) argue, the closed looping in metals manufacturing can be considered to be at such a degree that, perhaps along with paper and textiles, it is the most green or mature of metabolisms (Frosch & Gallopoulos, 1989; Szekely, 1996; Frosch et al, 1997; Sagar & Frosch, 1997). The implications derived from the energy hypothesis are perhaps the most pertinent. As the energy pattern rapidly increases early in development, peaks, declines and plateaus, efficiencies are expected not only in the amount of normal energy required to process the metabolite but also the amount of manual labour. As can be seen in figure 4.4 (above) the number of people employed in Sheffield's traditional manufacturers has dramatically declined in recent years. The problems in South Yorkshire, as seen in the opening paragraphs, are primarily related to employment in the region, as well as the knock effects this creates.

The metals' manufacturing metabolism is considerably mature, and as such demonstrates a good deal of diversity at several levels of aggregation. There are two main implications derived from the diversification hypothesis. The first is that although a high diversity index ensures stability at the level of the system, the competition at the micro-scale, however, creates an uncertain and unstable environment as Moffat (1996) indicates. This would suggest that although there is inherent uncertainty at the level of the firm, a mature metabolism should ensure stability at the level of South Yorkshire's socio-economic system. However, this contradicts the actual situation, which brings us to the next implication. With a globalised metabolism, not only are the micro-units, the firms, subject to intense competition, but also the next levels of aggregation, say, for example, regional production systems. This also appears to be a strong driving force behind South Yorkshire's decline. One final problem with South Yorkshire that concerns the diversification hypothesis is the lack of between-industry diversification. This is perhaps due mainly to the rapidity of the regions decline. A region that dominated the steel, metal goods and engineering sectors, perhaps needed no incentive to develop other sectors. However, as the metabolism globalised, and uncertainty and instability increased, other sectors that could potentially uptake the excess energy (labour) were far too immature (see figure 4.7). This is reflected in the local governmental regeneration strategies (see, for example, SFP, 1999a).

The organisational life histories and selection pressures hypothesis is particularly relevant to the region's present problems and is perhaps the most useful as it can be applied at the level of the firm (the micro-units). In terms of both this hypothesis and the problems in South Yorkshire, interpretation is a complicated task and beyond the scope of this chapter (however, see Tweedale, 1995). Very generally, South Yorkshire, although earlier in development readily embraced change, particularly innovative products, processes and organisational structure, later in the region's development there was a strong resistance to change, especially labour saving practices (see, for example, the 'Sheffield Outrages' - Pollard, 1959). The twice nationalisation (and de-nationalisation) was aimed at solving the issues of organisational and structural re-engineering. The main result, however, was a rapid decline in both employment and consequently regional socio-economic indicators.

Another argument (e.g. Tweedale, 1995) is that although Sheffield led the world in innovative product, process, and organisational development, at some point, perhaps related to the shift in practices that the two World Wars demanded (i.e. armaments), began suffering from foreign competition. Perhaps the resistance to change was physical, as in existing infrastructure (machinery), cultural (worker pride) and/or political (e.g. trade-unionism). Nonetheless, there is growing evidence (e.g. McCarthy, 1995a; Lowe, 1999) that organisational and structural forms are still lagging behind competition. The organisational life histories and selection pressures hypothesis indicates that organisations that are open, honest, willing to co-operate and collaborate and are more subservient to the system are likely to be more successful particularly in mature metabolisms.

The punctuated systemic control concept (the homeostasis hypothesis) is interesting in terms of the regeneration concept. This hypothesis is concerned with the processes involved in evolution and development and the constant and never ending feedback processes. In terms of the hypothesis, the idea of regeneration (political in origin) is nothing more than a part of the natural systemic developmental pattern. The energy, resources and activity generated by the regeneration idea, however, are important catalysts in bringing the system back in line with normal developmental paths, and should perhaps be referred to as a *developmental catalyst*. One important assumption contained within this hypothesis is that evolution and development are continuous processes. Change is the norm and should be both embraced and planned for. If this were the case, regeneration would ultimately be unnecessary.

4.6. Further Research Directions

The N-ET model was also developed with two practical objectives in mind. The first was to create a framework within which both evolutionary industrial networks of a sustainable nature (as well as the regional economy) can be represented and understood. This may serve as guidelines with which regional/national policy and decision makers can follow, particularly in guiding decisions and supporting activities in energy trends, closed-looping, diversification, and selection pressures.

The second objective is to use the model to develop complimentary novel classification schemes and 'blueprints' for organisational change initiatives. The sustainable development of regional economic systems are a manifestation or an emergent phenomenon resulting from the decisions that are made at the level of individual actors and the consequent changes seen at the level of the organisation.

Several classification techniques exist, similar to those used in biological taxonomy, organisational systematics, and functional classifications, which would help with benchmarking. However, many of these are considered to lack objectivity (McCarthy & Ridgway, 2000), and none refer to the science of classification. Nonetheless, research in this area is beginning to be conducted. Cladistics is an evolutionary classification scheme that not only describes the attributes of existing entities but also the ancestral characteristics. This method of classification may be very beneficial for change initiatives as existing manufacturing organisations can deduce what characteristics need to be added or dropped to change, for example, from a 'modern craft system' to a 'pseudo lean producer' (McCarthy, Leseure, Ridgway & Fieller, 1997). The work on this, following on from research by McCarthy et al (1997), Leseure (1998; 2000), and Goh (2000), constitutes the content of the remainder of this thesis beginning with the next chapter. This research is intended to help traditional manufacturers to make the step changes required to sustainably evolve in today's economic climate.

However, manufacturing cladistics suffers from the same problem with industrial ecology in that there is a conceptual disconnect between natural and anthropogenic systems. The N-ET model, through its argument of homology, introduces scope for increasing understanding of the evolutionary transitions needed for existing firms to remain competitive in mature metabolic systems. There now exists a justified opportunity to benchmark organisational structure and function. Classification research, as mentioned above, also compliments the regional perspective by analysing the activity at a lower level of aggregation.

With the models developed in this and the previous chapter in mind, the classification approach may also be taken further and incorporate evolutionary systems modelling techniques enabling the simulation of the evolution of manufacturing technologies and practices. As mentioned before, major obstacles to sustainable industrial development are the barriers that exist during implementation and technology transfer. An evolutionary framework would create knowledge and better tools of analysis that could potentially reduce the barriers to sustainable technologies and practices in manufacturing. By identifying sustainability characteristics, such as life cycle analysis, waste minimisation and energy efficiency schemes, and synthesising them with more traditional manufacturing characteristics, such as different production systems, factory layouts, and levels of automation, uncertainty and risk could be reduced and opportunities and barriers could be identified.

4.7. Conclusions

The N-ET model of the industrial development of metals manufacturing developed an argument of homology rather than the usual analogy by drawing primarily from non-equilibrium thermodynamics and complex systems thinking, systems ecology, industrial ecology, and networking theory. The model hypotheses focus around homologous patterns found in both natural and industrial systems in energy intensities, production and recycling, diversification, organisational life histories and selection pressures, and systemic stability. Existing data and literature were used to provide preliminary supporting evidence. However, fundamental qualifications for the model's applicability as well as some potential flaws were highlighted. It is essential that further research be conducted to either support or refute the hypotheses and model. The implications for South Yorkshire, in terms of systemic decline and subsequent sustainable regeneration were examined in the context of the model.

The model also represents a framework within which classification schemes of individual organisations can now be justifiably developed from ecological and biological principles, particularly industrial cladistics and functional classifications. Classification research is intended to enable the local SMEs to make the step changes needed to adapt and compete in today's globalised economic climate. An in-depth review of manufacturing cladistics is the subject of the next chapter.

CHAPTER 5 - MANUFACTURING CLADISTICS

5. Introduction

A common belief within manufacturing is that 'the only constant is change'. Manufacturing classifications have been developed not only as a means of classifying different organisations that exist but also, and perhaps more importantly, as a tool to both help deal with change, and use as a guide for organisational re-engineering. During the last decade research in manufacturing cladistics has accumulated rapidly (Todd, 1998). The manufacturing cladistics approach, which concentrates on the evolution of physical attributes, appears to be the most productive for classifying manufacturing types and for offering guidelines for change initiatives (e.g. McCarthy et al, 1997; Leseure, 2000; McCarthy, Leseure, Ridgway & Fieller, 2000).

The models developed in chapters 3 and 4, particularly the argument of homology, have increased justification for the application of biological techniques and concepts to anthropogenic systems – a conclusion reached in chapter 4. Classification research, by focusing on the activity of individual organisations, also compliments the regional perspective as to really understand the activities of regional networks, an understanding is also needed of the evolution of individual companies in the context of the decisions that are made. Change at the regional level is a manifestation of changes at this micro-level.

The original aim of this thesis was an attempt to provide a dual perspective of the development of sustainable regional networks (a macro perspective) and the evolution of sustainable individual organisations (a micro perspective) – with the former being a manifestation of the latter. To achieve this, the aim was to develop manufacturing classifications of the evolutionary history of sustainable manufacturing utilising new developments in manufacturing cladistics. However, as this research developed the aims of the thesis began to evolve and change and as further research directions were explored (documented at the end of this chapter) a different direction was taken. This direction nonetheless still utilises manufacturing classifications, which will be reviewed in this chapter, but also includes the idea of utilising and integrating evolutionary systems methodology (reviewed in chapter 6).

To fully appreciate developments in manufacturing cladistics, several additional areas linked to this research area require reviewing and clarification. Therefore, firstly, biological taxonomy is introduced and discussed, specifically, the impact of numerical taxonomy, biological classifications, and the notions underlying classifications. Particular schools of thought will be highlighted such as phenetics, phylogenetics, cladistics, evolutionary schemes, and functional classifications. General conclusions concerning biological taxonomy are also outlined.

Manufacturing cladistics, the main focus of the rest of the thesis, is discussed in more depth, and particularly tackles the problem of why classifications are constructed and how to construct a manufacturing cladogram. Examples of applied research including classifications of manufacturing complexity, management styles, the hand-tool industry, and the automotive industry are also given.

Before concluding the chapter, research recommendations in this area are highlighted. Further research identified includes: a) feasibility studies; b) a combination of classification schemes, specifically cladistics, which concentrates on physical form, and functional classifications, which is based on strategies for survival; c) the cladistic evolution of sustainable organisations (the original research aim); and, d) a combination of manufacturing cladistics and evolutionary systems modelling (the direction now taken in this thesis).

5.1. Biological Taxonomy

As biologists study life in all its forms, taxonomy and classification have been useful tools right from the beginning of this discipline. Managing all the information on all living entities, their genetics, form and behaviour, has been immensely helped through these techniques and as such the methodology has been refined to an extent that they are now integral aspects of biology. Evolution is central to the main classification methods. Indeed evolution and classification have helped shape understanding why an entity looks like it does and behaves in a certain way. However, before describing the main classification methods used in biology, it is necessary to highlight the discipline of numerical taxonomy.

5.1.1. Numerical Taxonomy

Numerical taxonomy is the process of grouping of taxonomic units, using numerical and statistical techniques, into groups or taxa based on attribute/character commonalities and differences. By using numerical and statistical techniques, the data must be in quantitative form. 'Operational taxonomic units' are the lowest common denominator, i.e. the individual entity. 'Identification' is the procedure of grouping individuals into groups or 'pigeon-holing'. The taxonomic characters (attributes, features, and variables are also common in the vocabulary and are to a point interchangeable) are essential to the classification and have two main purposes. The first function is that they are what differentiate between entities aiding the process of grouping. The second function is that they describe or indicate the relationship higher up the hierarchy.

Once data has been collected on the character states, they are subjected to statistical analyses. Firstly, a distance (or similarity) matrix is developed which displays both the entities and all characteristics, and more importantly the distance or similarity between entities. Several distance and similarity techniques or coefficients have now been developed including 'simple matching coefficients', 'Jaccard's coefficient', and 'Gower's coefficient'. Cluster analysis is then performed which summarises the information in the distance matrix. There are currently many available clustering techniques and these may be grouped in five categories:

- *Hierarchical techniques* – one group is formed initially then further groups are found from this, producing a hierarchy (Everitt, 1986)
- *Optimisation techniques* – these are partitioning techniques whereby groups are found through the utilisation of a clustering criterion (Cormack, 1971)
- *Density Searches* – these techniques identify clusters of data, gathered naturally, in 'metric space' (Everitt, 1986)
- *Clumping techniques* – these techniques allow for continuums in as much as the groups are not distinct and that an entity can be found in several groups (Aldenderfer & Blashfield, 1984)
- *Other techniques* – these techniques include Q factor analysis (Cattell, 1952), Latent Structure Analysis (Lazarsfield & Henry, 1968), principal component

analysis and factor analysis (the latter two are not strictly clustering techniques but ordination techniques).

To conclude on this section the following points can be made concerning numerical taxonomy. The first is that the techniques allow for the integration of data from several sources. The techniques are more efficient as the process is automatic and computerised. As the data is quantitative, discrimination is facilitated and it may be utilised by many different computer programs. Numerical taxonomy also helps the researcher in the understanding of the characteristics involved. More generally, the discipline feeds back on itself whereby the principles and purposes of classification may be re-examined and refined, and that theories, concepts and issues in biology and the evolutionary sciences may be evaluated.

5.1.2. Biological Classifications

One of the first questions asked by classification researchers is (e.g. Good, 1965; Cormack, 1971; Carper & Snizek, 1980; McCarthy et al, 2000): Why construct a classification in the first place? Good (1965) suggested four purposes:

1. For mental clarification and communication
2. For discovering new fields of research
3. For planning an organisational structure or machine
4. As a checklist.

Similarly, Haas et al (1966) argued that there were four advantages, i.e. that a realistic classification could:

1. Refine hypotheses
2. Determine validity and utility based on logical and intuitive reasoning
3. Provide a basis for prediction
4. Specify populations from which samples could be drawn.

Classification, as a science, essentially began with biologists. There are two main biological principles – phenetics and phylogenetics. From these, three main classification disciplines have emerged – the phenetic, evolutionary and cladistic approaches. These schools can be thought of as lying on one dimension – the evolutionary scale. Phenetics is non-evolutionary and lies at one extreme. Cladistics in based purely on evolutionary principles (a purist approach) and lies at the other extreme. Evolutionary classifications are a synthesis of phenetics and cladistics and lie somewhere in the middle of the scale.

In recent years another classification approach has been developed by Grime (1998) and is termed functional classifications. Functional classifications are very different to all other classification methods as the entities' strategies for survival are the main focus. But before these classification techniques can be explored, the notion of classification, i.e. the nominalistic and essentialist perspectives need to be highlighted.

5.1.3. Notions

The nominalistic view, the oldest notion of classification (McKelvey, 1982), argues that because all entities are essentially different in some way or another, it is impossible to strictly classify, and distinguish between any groups. Furthermore, if a 'loose' classification is made then it is argued that there should be no distinction between living and non-living objects. The essentialist perspective, dating as far back as Aristotle, however, argues that the living have a reality that reveals properties or attributes that may be observed. Essentialism is the identification of these attributes and subsequent development of a taxonomy. With essentialism three aspects of a living entity may be known – the essence, the definition and the name. Many now regard essentialism as the most fundamental philosophy behind classification.

5.1.4. Phenetics and Phylogenetics

The phenetic and phylogenetic principles in biology have produced the three main schools of biological classification theory – the phenetic, cladistic and evolutionary theories. Phenetics investigates the similarities between objects/entities and ignores or dismisses the potential evolutionary link, i.e. entities sharing a physical similarity are grouped and entities having physical differences sorted into separate groups (Ridley, 1993). Any physicality may be used, for example, bones, limbs, and even colour. Some researchers argue that phenetics is synonymous with numerical taxonomy as both disciplines were developed at the same time and were somewhat intertwined (McCarthy, 1995a).

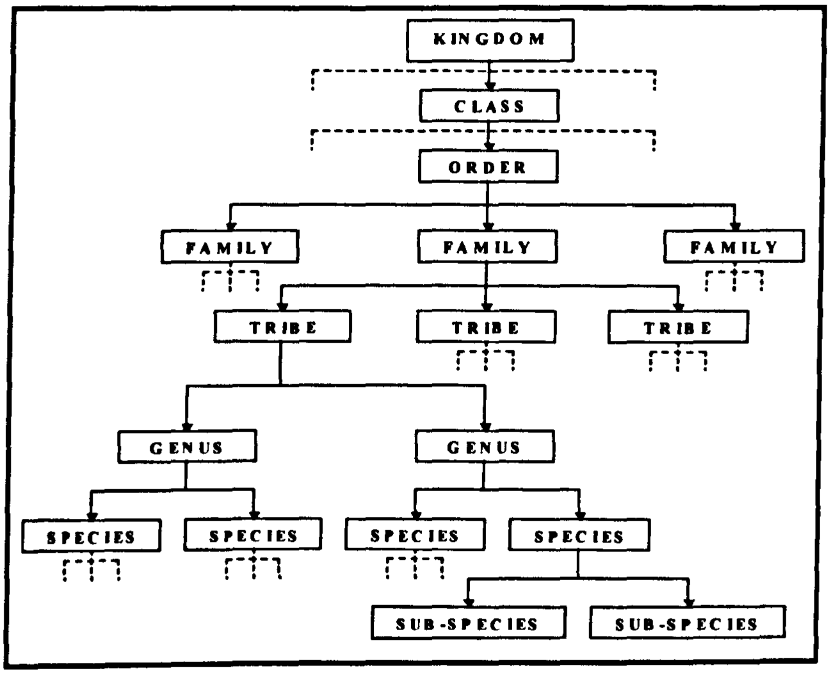
Phylogenetics, on the other hand, is based on evolution and ancestral commonality – similarities in physical form is consequential (Ridley, 1982). The classification process produces a hierarchy of branches commonly known as the 'evolutionary tree'. The difference between phenetics and phylogenetics can be seen with the following example (Ridley, 1982). A phenetic classification developed for barnacles, limpets and lobsters would group the barnacle with the limpet as they share more physical commonalities and the lobster would be placed in a separate group. However, as the evolutionary history of the three reveals that the barnacle's and limpet's ancestral commonality is further back in time than the lobster's and barnacle's ancestral commonality, the lobster would be grouped with the barnacle and the limpet would be placed in a different group. The difference between the physical and ancestral commonalities for the crocodile, lizard and bird is another good example of the difference between the two approaches (McCarthy, 1995a).

5.1.5. Cladistics

Ridley (1993) and Wiley et al (1991), after reviewing the three schools, i.e. phenetic, cladistics and evolutionary classification disciplines, to assess their ability to construct natural and objective classifications (rather than artificial and subjective classifications), concluded that only cladistics could fully satisfy these criteria. Using evolution as an external reference point (evolutionary history cannot be changed), classifications will be unique and unambiguous. Cladistics has recently become the most accepted approach in biology and as such is the most appropriate starting point when constructing manufacturing classifications (McCarthy et al, 1997; 2000).

The word 'cladistics' is a derivative of the Greek term 'klados' meaning branch and was developed by Hennig (1950) while working on phylogenetic classifications. Fitch (1984) argues that cladistics is the identification of evolutionary links between taxa. Data is typically drawn from surviving taxa. Cladistics is an evolutionary classification scheme that not only describes the attributes of existing entities but also the ancestral characteristics. In other words, the cladistic approach investigates the evolutionary links between entities and studies common ancestors. Therefore two species may be placed in the same group if they share a recent ancestor, whereas they may be placed in different groups (but still the same family) if the ancestor is more distant. The more distant the entities, the further apart their respective positioning in the classification (see figure 5.1). More in-depth principles of cladistics are introduced in the manufacturing cladistics section (section 5.2. below).

Figure 5.1. A taxonomic hierarchy presented dendrogrammatically (adapted from McCarthy, 1995a)



5.1.6. Evolutionary Classifications

The evolutionary classification approach is an attempt to integrate both the phenetic and cladistic approach, drawing on the advantages of both whilst minimising the disadvantages (McCarthy, 1995a). Evolutionary classifications are based on whether the taxonomic characters have homologous or analogous characteristics when compared to their taxonomic group. Homologous characters are found in both the species and their common ancestor whereas analogous characters may be found between species but not in the common ancestor. Based on this, three types of groups may emerge - groups that are either monophyletic, paraphyletic or polyphyletic. A taxon is said to be monophyletic if all species originated from a single ancestor (and not to any other species in any other taxon). The common ancestor is also included in the group. Members of a polyphyletic group may have derived from two or more ancestors, and thus may not be common to all members. The common ancestors are not included in the taxon. A paraphyletic group does include the common ancestor but does not include all other descendents (on different branches) of the common ancestor.

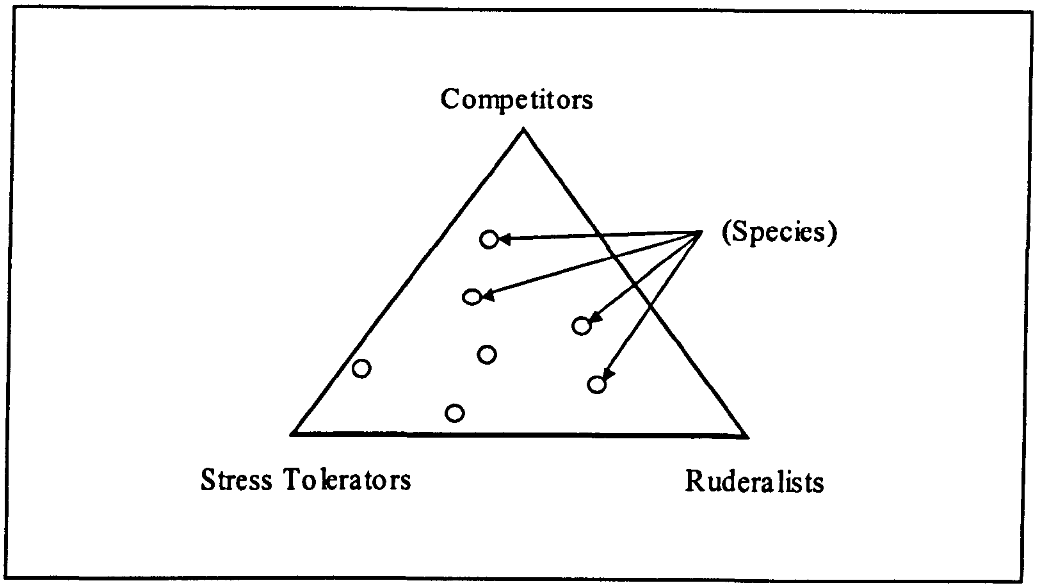
5.1.7. Functional Classifications

Functional classification is a fairly recent development in ecology (Grime, 1998). Functional and cladistic classifications are thought of as complementary disciplines by many biologists and philosophers, since their results describe different properties of species. Whereas cladistics concentrates on identities, functional classifications focus on strategies for survival (Tsinopoulos & McCarthy, 1997; Leseure, 1998; McCarthy et al, 2000). Grime (1998) developed such a classification in plant ecology termed the CSR model. The model assesses species in terms of competition, stress and ruderalism (Grime, 1974; 1977; 1979b; 1979a; 1981; 1984; 1986; 1998). The environment plays a central role and is measured along two dimensions - stress and disturbance.

Stress is defined as the limitation put on resources needed by the species/organisations to survive, for example, it is the lack of nutrients, light, and appropriate temperatures (Grime, 1998). Disturbances are occasional, but serious, environmental events. In plant ecology examples include fire, frost, and human interventions (e.g. trampling).

Species are classified according to their strategies for survival. Competitors (C) typical thrive in environmental conditions that are optimal, i.e. without any stress or disturbance. Competitors are typically ruthless, competing to be the biggest, tallest and most dominant. If environmental conditions become stressed the competitors' strategy for survival becomes less effective. Stress tolerators (S) typically emerge and take a lead over competitors becoming the most dominant species/organisation in that particular environment. If the frequency of environmental disturbance is high, ruderalists (R) begin to thrive and become the prevailing type. These types are of course extremes, species/organisations may lie anywhere between the three (see figure 5.2).

Figure 5.2. Species/organisations' place on the CSR model (from Grime, 1998)



5.1.8. Biological Taxonomy: Conclusions

From the review of biological classifications the following conclusions can be made. Research in biology has led to the most comprehensive classification techniques available, particularly as most have incorporated numerical taxonomy. Numerical taxonomy, through the use of quantitative data, increases objectivity, efficiency and discrimination between entities. It also increases understanding of the classification process while providing the opportunity to re-evaluate and re-examine the theories that the classification is based on. Work on classification has led to the development of three main schools of thought – phenetics, and from the phylogenetic school, cladistics and evolutionary classifications, all of which incorporate the underlying philosophy of essentialism. From the review, it can be concluded that, in terms of manufacturing and industrial classifications, cladistics provides the most appropriate vehicle with which to classify. Having said this, functional classification, which focuses on strategies for survival, also offers a novel approach to classification particularly if combined with cladistics. The next section reviews the research to date in manufacturing cladistics, particularly in constructing a manufacturing cladogram, some industrial and manufacturing applications, problems and drawbacks of the approach that need to be overcome, and further areas of research that can be exploited.

5.2. Manufacturing Cladistics

Returning to the question: why construct a classification in the first place? One of the answers provided by Good (1965) was 'for planning an organisational structure or machine'. This was one of the main drivers for developing manufacturing cladistics. When classifications are applied to manufacturing and industry, the pioneers of this approach, McCarthy et al (2000: 78), argue that a classification 'would facilitate the storage, alignment and development of structural models of manufacturing systems [that] . . . would provide researchers and consultants with a generic library of structural solutions for enabling manufacturing systems to maximise their operating effectiveness'. That is, if a cladogram were constructed comprehensively enough it would provide a blueprint with which manufacturers could use as a guide to help in changing their operating structure to gain competitive advantage.

5.2.1. Constructing a Manufacturing Cladogram

McCarthy et al (1997), adapted from Ross (1974), lists seven basic steps in constructing a manufacturing cladistic classification:

1. *Determine the clade (taxon).* In terms of manufacturing this would be the industrial sector – the organisation of interest as well as its common ancestors
2. *Determine the characters.* These are variables, features or attributes from which comparisons may be drawn. The character, however, must be significant in evolutionary terms
3. *Code the characters.* This step in the process deals with the labelling of characters, so that decisions can be made whether they exist in the forms of organisation under study
4. *Ascertain character polarity.* Characters may be primitive or derived. These distinctions are fundamental in the construction of the classification. Primitive characters are present in the ancestors whereas derived characters are not present in any ancestral species

5. *Construction of the conceptual cladogram.* This stage is concerned with constructing the cladogram from historical accounts (typically extinct or rare/unavailable species). This is usually a 'best estimate' of the evolutionary relationships
6. *Construction of the factual cladogram.* This is involved with contemporary organisations. Data collected consists of material from, for example, interviews, questionnaires, observations, company records, annual reports, and business plans. The data from this is then combined with the conceptual cladogram, producing a full cladogram
7. *Decide taxa nomenclature.* This stage deals with the labelling or naming of the manufacturing systems. This should conform to the principles of biological nomenclature. In short, labels should convey the essence of the entity, convey the main characters, indicate the position on the cladogram, be written in Latin terms, be unambiguous, and ensures universal communication.

To date the cladistic approach in industry has been applied to the complexity of manufacturing organisations (McCarthy, 1995a), to management techniques (Goh, 2000), the hand-tool and the automotive industry (McCarthy et al, 1997; Leseure, 1998; McCarthy et al, 2000). These applications are reviewed in the next section.

5.2.2. Cladistics: Manufacturing Complexity

McCarthy (1995a), in perhaps a seminal thesis, initially began exploring new competitive trends in the rapidly globalising economy and how these trends have affected the local manufacturers of the South Yorkshire region. The thesis also explored several change initiatives aimed at promoting and sustaining innovation and organisational re-engineering (e.g. just-in-time, total quality management, and business process re-engineering). One of the main conclusions came to was that if a consistent classification scheme was developed, a 'blue print' of manufacturing systems could be referred to when implementing change initiatives – a reference model to help achieve 'best practice'. This is the first piece of research into manufacturing cladistics.

The approach taken was the evolution of manufacturing complexity. Four main aspects of complexity were examined through questionnaires, interviews, and research into company records. The four dimensions of manufacturing complexity and an explanation are as follows:

- *Product complexity* – this dimension indicates the different degrees of difficulty in the assembly of the product, including the number of product parts, the number of different parts, number of connections, technology used (i.e. mature technology through to cutting edge or key technology), and the product versions and accompanying volumes
- *Open complexity* – this dimension assesses the environment in which the manufacturing system is embedded and includes issues such as government regulations, public opinions, market uncertainty, market stability, competition, suppliers, and customers
- *Static complexity* – this dimension gauges the degree of interconnectedness of the different manufacturing constituents. Factors including organisational structure, flow of products, number of departments, management levels, different job titles, and the number of machines, represent static complexity
- *Dynamic complexity* – this dimension examines activities, processes, and operations in the organisation. Indicators such as production volume and variety, new product introductions, degree of automated production, the flexibility of operations, processing time, scheduling rules and scheduling decisions, constitute dynamic complexity.

Following on from the procedure in which cladograms are constructed (section 5.2.1.) and after cluster analysis, four main clusters of manufacturing organisations were proposed and accordingly named *Distinctus-densus, Distinctus-certus-parvus, Distinctus-compositus-impeditus,* and *Distinctus-multiplex.* Dinstinctus-densus (group 1) are characterised by family or privately run companies that have local/regional market scope and typically make-to-order. They have relatively little suppliers and customers. Competition is average and the event of product substitution is low. The technology level is quite low and they tend to employ near net shape forming techniques (basic processes, e.g. in forging, pressing and fabrication). In summary, they have low levels of open, product, dynamic and static complexity.

Distinctus-certus-parvus (group 2) are also typically make-to-order companies but unlike the former group are heavily influenced by their environment (e.g. regulations). The threat of product substitution is low with low levels of new competition. The production process, however, has little repetition with frequent changes in products. The process routes are typically complicated with long lead times but low volumes and scheduling. Compared to the other groups the companies were quite young and as a consequent had not developed a formal structure. In summary the companies in this cluster had moderate levels of open complexity, the highest levels of product complexity, an average rating in dynamic complexity and low levels of static complexity (but a little higher than Distinctus-densus).

Distinctus-compositus-impeditus (group 3) all have similar histories and make the same products for the same markets with similarly sized manufacturing systems. Hence market uncertainty was low. The maturity of the industry is high, associated with high levels of competition from foreign manufacturing systems with cheaper products. The market scope is international with very large and demanding customers. Product volumes and variety along with the times of processing have low levels whilst scheduling has high values. These companies typically have high numbers of departments and management levels structured hierarchically. Thus in summary, companies in this cluster have a high level of open complexity, an average product and dynamic complexity, and relatively high level of static complexity (higher than group 1 and 2 but less than group 4).

Distinctus-multiplex (group 4) is characterised by relatively old, large multinational companies selling brand name products with the furthest market reach, a high number of customers, market instability and a heavy influence from the environment (public opinions). The influence from customers and suppliers is low with a relatively uncomplicated supply chain. There is also a low threat of product substitution. Products are assembled using simple components, technologies, procedures, and dedicated automation, with high volume but low product variety. The companies have the largest manufacturing systems indicated by turnover, plant size, number of job titles, machines and workers. There is a high degree of differentiation both vertically and horizontally. In summary then, this group has above average open complexity, low product complexity, average dynamic complexity, and the highest level of static complexity.

In summary of the research by McCarthy (1995a) it is not so much the classification scheme developed that was important but the process of constructing the manufacturing cladogram. Much of the thesis was concerned with the development of this process, reviewing the main work in the disciplines of organisational systematics, numerical taxonomy and biological classifications. Another important feature of this research was the procedural translation to manufacturing and industry and to the social sciences.

5.2.3. Management Techniques

Manufacturing cladistics was also utilised in an attempt to firstly understand the evolution of management styles through the literature (see table 5.3) and secondly to give an example of how to benchmark management styles and the relative position of an organisation on route to total quality management (Goh, 2000). There were two important phases in this research based on one questionnaire survey. The first was to construct a cladogram of general management styles. The second was to construct a cladogram of the evolution of management styles in ten organisations local to the South Yorkshire (UK) region as well as one Japanese firm. To construct both cladograms, computer software termed MacClade (version 3), developed by Maddison and Maddison (1992), was utilised (Goh, 2000). The software analyses character evolution and the phylogenetic hypotheses. Data was collected through a questionnaire survey that explored the common characteristics of management styles (table 5.4 lists these characteristics).

Table 5.3. The evolution of management styles (from Goh, 2000)

Pre-1770	*Pre-industrial Management*	Military management – chain of command, delegation of authority, staff, and unity of command
1771-1858	Robert Owen	Beginning of primitive personnel management and human resources (performance related)
1792-1871	Charles Babbage	Classical school of management – profit sharing plans and bonus schemes, division of labour
1880	*Scientific Management*	Division of labour, efficiency, education – the analysis of human and mechanical jobs
1856-1915	Frederick W Taylor	Time studies, 'first class man', differential piece-rate, labour division, management hierarchy
1861-1919	Henry L Gantt	Modification of Taylor's method – bonus schemes, progress charts (production, cost, quantity)
1868-1924	Frank B Gilbreth	Motion studies – 'quest for one best way', improve productivity and reduce effort, work-breaks
1878-1972	Lillian M Gilbreth	'Psychology of management' – training and job rotation to boost morale
1896	*Administrative Management*	The study of organisation structure and management
1841-1925	Henri Fayol	Five functions of management – planning, organising, command, co-ordination and control
1864-1920	Max Weber	Bureaucratic organisation based on rational legal authority
1886-1961	Chester Barnard	Co-operative system – willingness to co-operate, a common purpose, and communication
1884-1957	James Mooney	Three principles of organisation – co-ordination, the scalar principle and function principle
1891-1983	Lyndall F Urwick	Managerial framework – scientific investigation, forecasting, plans, and operations
1930	*Human Relations*	The human factor and its influence on productivity
1868-1933	Mary Parker Follett	Importance of the group, conflict resolution, depersonalised authority, group synergy
1880-1949	George Elton Mayo	Hawthorne plant study – human collaboration, improved working conditions
1940	*Modern Era*	Management science (mathematical models); Behaviour science (human resource management)
1906-1964	Douglas McGregor	Theory X and Theory Y
1908-1970	Abraham H Maslow	Theory of motivation & hierarchy of needs – physical, safety, social, esteem and self-realisation
1923-	Chris Argyris	Personality versus organisation – incongruency; job enlargement, employee participation
1923-	Frederick Herzberg	Motivation theory – hygiene factors and motivation factors
1940	Operations research	A quantitative basis for decision making to solve production problems, schedules and costs
1960	Decision theory	Combination of quantitative tools and economic concepts of utility and choice
1968	Systems theory	Framework – internal and external environmental factors as an integrated whole
1970	Contingency theory	Solution to a problem depends on the factors and the situations – no two solutions are the same
1950	Total Quality Management	Quality of work, service, information, process, division, company, objectives and people

Table 5.4. Characteristics of management (from Goh, 2000)

1. Management commitment to quality
2. Management commitment to productivity
3. Management commitment to the customer
4. Management leads by example
5. Organisation is pyramid shaped
6. Jobs are directed towards a common goal
7. Unity of command: One supervisor per worker
8. Emphasis solely on machinery
9. Emphasis solely on human resources
10. Resources co-ordinated for maximum efficiency
11. Communication of company policy and future developments
12. Good working relationship between management and workers
13. Centralisation of authority
14. Scalar chain of command
15. Positional power
16. Equity: Justice and kindness is shown in management
17. Management commitment to employee training
18. Employee training – financial commitment
19. Scheduled management training
20. Scheduled employee training
21. Mutuality of interests
22. Management actively ensures employee motivation
23. Employees updated on company progress
24. Management ensures good work conditions
25. Policy to ensure employee welfare
26. High literacy among workers
27. Job rotation to avoid monotony
28. Co-operation is fostered
29. Employment in-line with future needs
30. Inter-department co-operation
31. Intra-department co-operation
32. Workers are self-disciplined
33. Subordination of interests
34. Job security
35. Espirit de Corps (Teamwork)
36. Work improvement teams
37. Specialisation of labour
38. Highly skilled workers
39. Detailed work instructions are given
40. Worker responsible for own input
41. Daily performance chart used to monitor performance of workers
42. Employee participation in decision-making
43. Level of self-initiative is encouraged
44. Employees have opportunities for growth and development
45. Effective communication among workers
46. Good level of communication between management and workers
47. Active search for customer feedback
48. Monitor customer satisfaction
49. Fixed customer contact, employee per customer
50. Communication of customer complaints
51. Customer complaints are communicated to the relevant worker
52. Continuous improvement of product
53. Continuous improvement f service
54. Benchmarking of customer satisfaction
55. ISO9000 accreditation
56. Documentation of work procedures
57. Working closely with suppliers
58. Formal cost accounting maintained
59. Record keeping for future reference

The questionnaire was divided into principles, their components and finally the characteristics. The principles and components are as follows:

- The **principle of management commitment** the components of which are:
  - Commitment
  - Organisational culture
  - Management styles
  - Training and development
- The **principle of employee participation**, the components of which are:

    - Employee satisfaction
    - Motivation and employee involvement
    - Communications
- The **principle of customer focus**, the components of which are:
    - Customer satisfaction
    - Continuous improvement.

The survey was completed through semi-structured interviews with a senior manager of ten companies local to the South Yorkshire region (UK) and one company based in Japan. Fifty-nine characteristics were identified and through the use of the MacClade software two cladograms were constructed. The first cladogram represents the evolution of the general management styles with six main groups emerging (see figure 5.3). The second cladogram represents the evolution of management of the 11 organisations participating in the questionnaire study (see figure 5.4).

Figure 5.3. A cladogram of management styles (adapted from Goh, 2000)

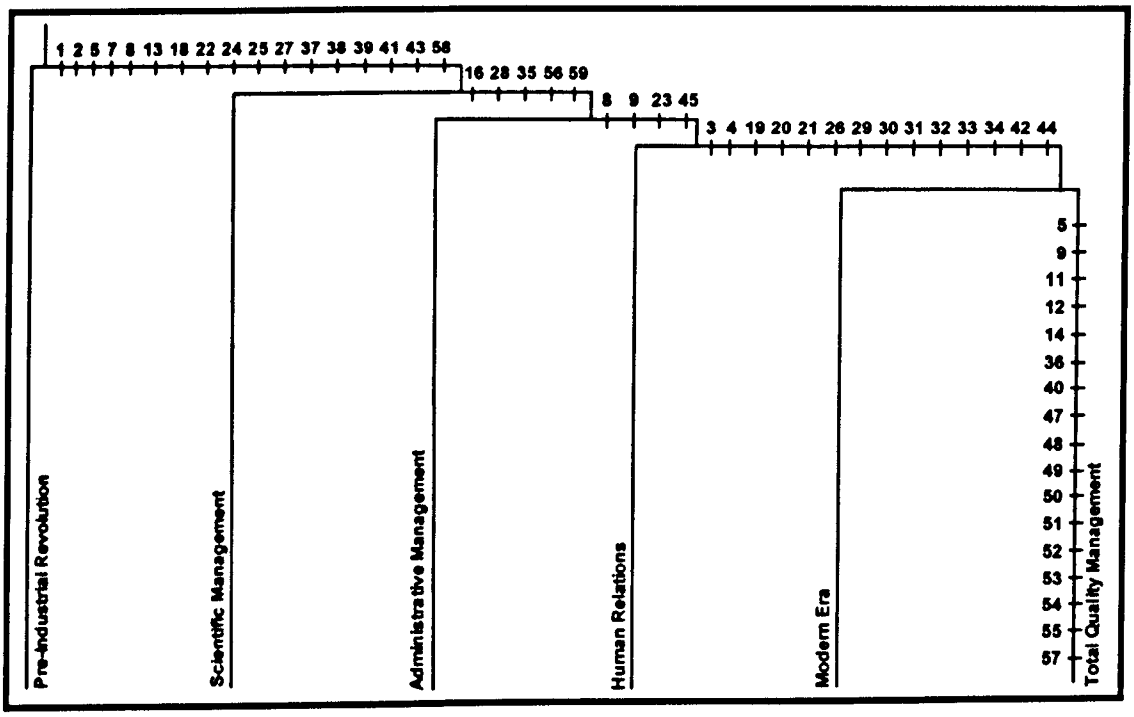
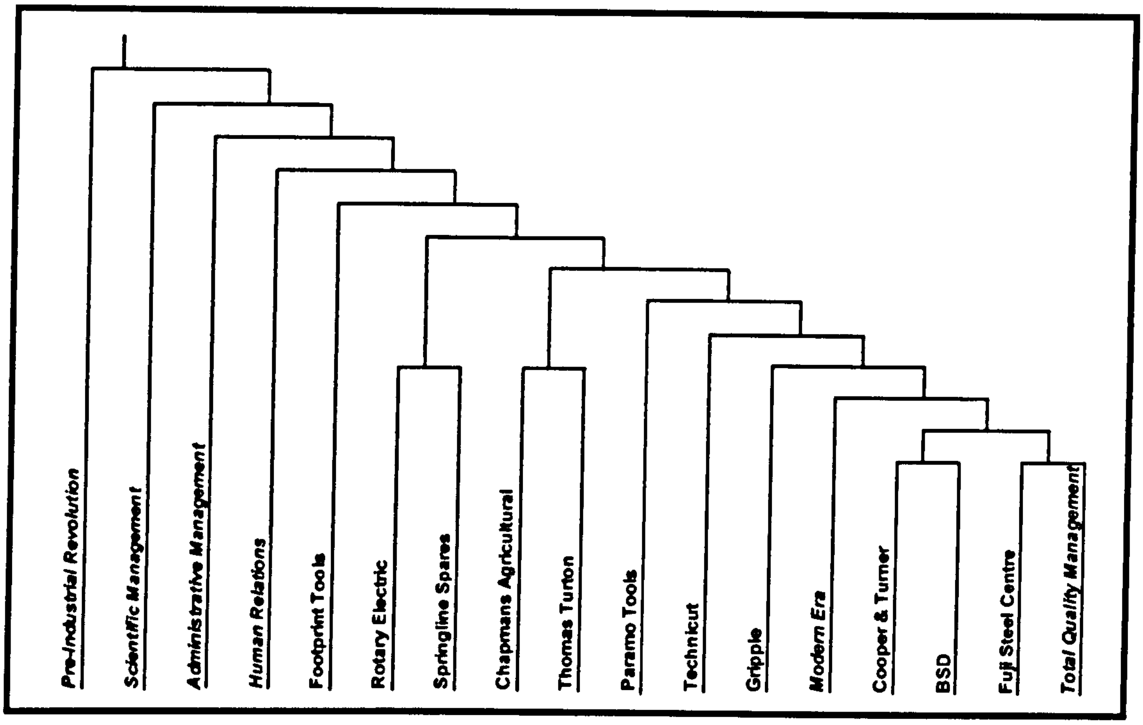


Figure 5.4. A cladogram of company management styles (adapted from Goh, 2000)



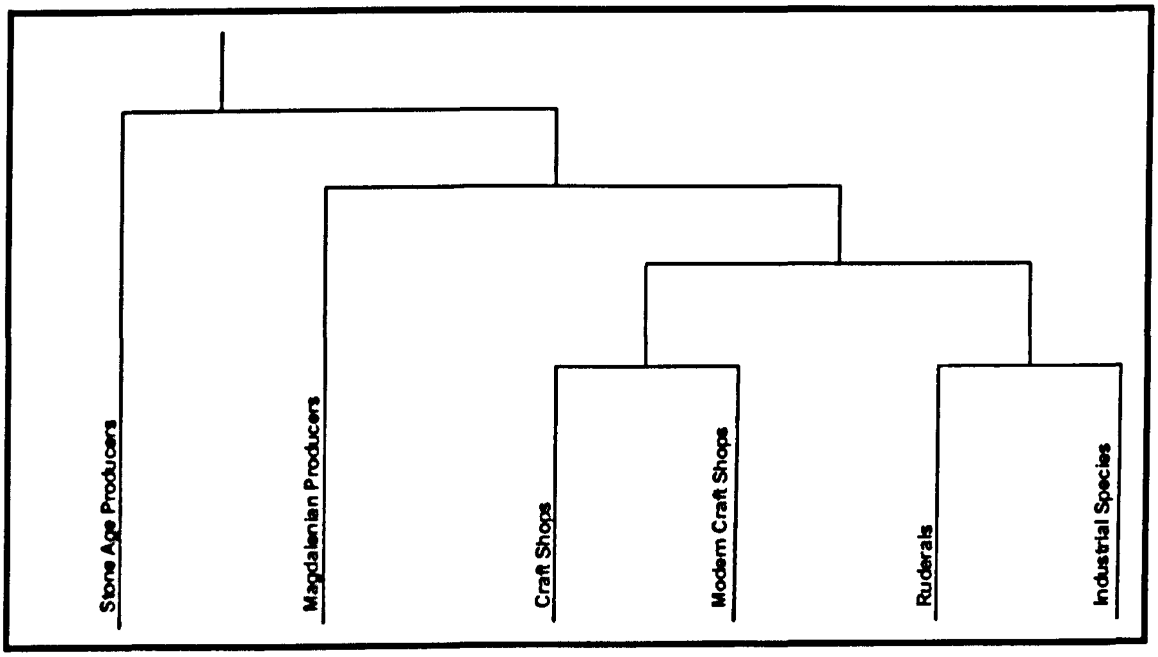
Although this research produced cladograms that at first glance were attractive in their simplicity there are a number of faults with the research. The first problem is that, in contrast to McCarthy's (1995a) manufacturing complexity, a cluster analysis was not carried out or if it was there was no indication in the research. Another problem was that only six main phases of management styles were produced – the sub-groups, seen in table 5.3, were not included. If these sub-groups were included a richer description of management style evolution would be available.

In examining the cladograms produced (see figures 5.3 & 5.4) there are several further flaws that need to be clarified. For instance, characteristics 5, 8 and 9 have been included twice. For example, characteristic 5, *organisation is pyramid shaped*, first emerged on the branch leading off to the *Scientific Management Style*, but also re-appeared on the branch for the *Total Quality Management Style.* The flaw may only be typescript error (in that TQM advocates a flatter organisational structure rather than pyramidal or hierarchical) but is nonetheless misleading. Another problem is that characteristics 6, 10, 15, 17, and 46 are completely missing from the cladogram. So of the 59 characteristics identified, only 54 have been included in the cladogram. There are no explanations given in the research. The flaws of this research also extend to the company management cladogram (see figure 5.4), in that there are no indications of the introduction of different characteristics, leaving the cladogram with little utility. Having said this, however, the cladistics was only a small part of the research conducted by Goh (2000) and was only a demonstration of the utility of the approach and as such succeeded. Clearly, further research is required.

5.2.4. The Hand-Tool Industry

Building on the work of McCarthy (1995a; 1995b), Leseure (1998; 2000) presented the results of a cladistic classification of the hand-tool industry. Important aspects of this research include the research methodology, the phylogeny of the hand-tool industry, and descriptions and cladistic classifications of pre- and post-industrial revolution, hand-tool manufacturing species. Based on this work, directions for manufacturing innovations and strategies were also recommended. To construct the cladistic classification, several sources of data were sought including company archives and publications, historical accounts, expert interviews, visits to companies, discussions with the Federation of British Hand-tool Manufacturers, and a questionnaire survey. Two stable cladograms were constructed. The first is a representation of pre-industrial evolution of hand-tool manufacturing (see figure 5.5).

Figure 5.5. Pre-industrial hand-tool cladogram (adapted from Leseure, 1998)



As can be seen from figure 5.5, six species of pre-industrial, hand-tool manufacturers were identified. For more in-depth discussion of these species refer to the research of Leseure (1998). The next evolutionary step was the industrial species and appeared at the time of the industrial revolution. Leseure's (1998; 2000) cladogram of this division (see figure 5.6 and table 5.5) is the most relevant as it describes species of hand-tool manufacturers of the modern era.

Figure 5.6. Cladogram of the modern hand-tool industry (adapted from Leseure, 2000)

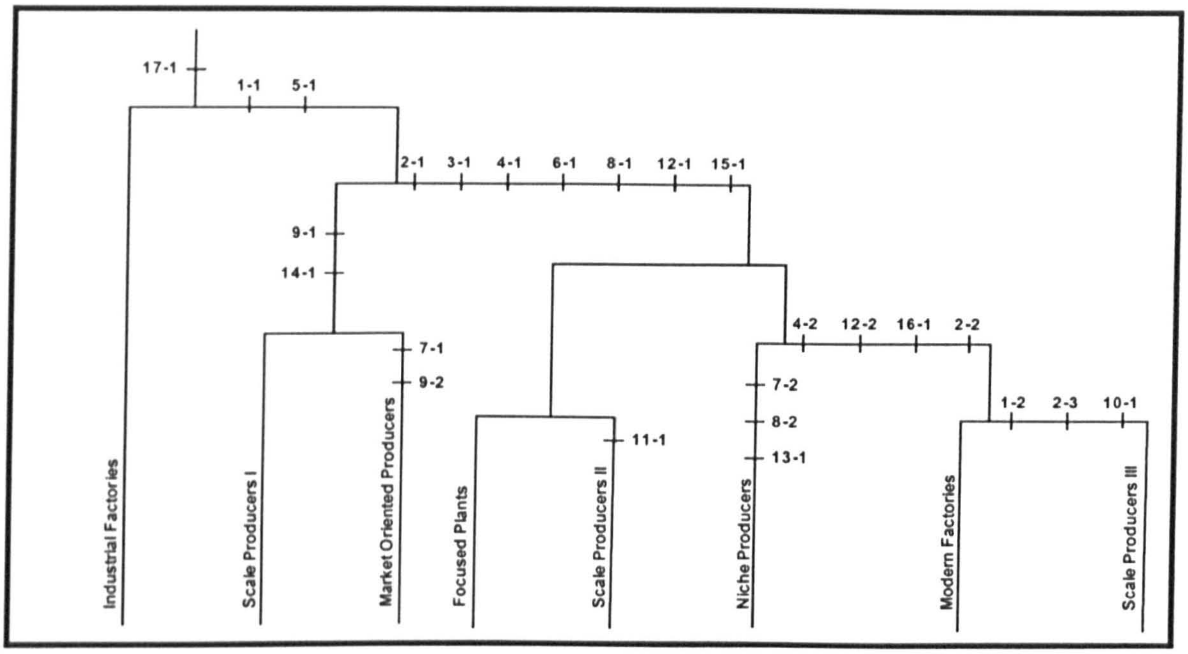
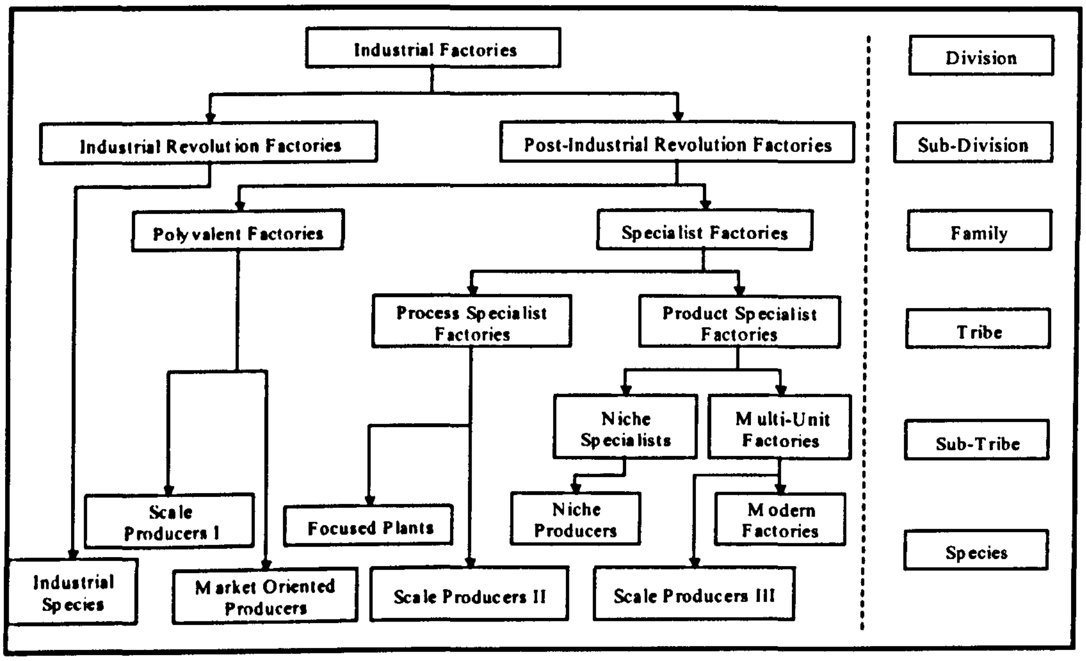


Table 5.5. Characteristics of the modern hand-tool industry (from Leseure, 1998)

Character	States	Character	States
1. Specification of product route	0: No specified routes 1: Fixed routing	9. Macro layout II	0: No macro layout 1: Pure functional layout
2. Number of product routes	0: Any 1: Unique 2: Multiple routes, one route for one product	10. Joint process centres	0: Some 1: Eliminated
3. Macro layout I	0: Functional layout 1: Product-based layout	11. Production flow	0: Discrete 1: Hybrid 2: Continuous
4. Micro layout for product-based layout	0: Not applicable 1: Inner process centres 2: Product lines	12. Product variety	0: Multiple families 1: Single family 2: Independent multiple families
5. Nature of activity	0: Make to stock 1: Adaptive make to stock	13. Production scale	0: High volume 1: Medium size batches
6. Process diversity	0: High diversity 1: Limited process diversity	14. Low volume items	0: Processed or outsourced 1: Avoided or eliminated
7. Product range consistency	0: Dictated by manufacturing capability 1: Dictated by market requirements to maintain a brand name 2: Niche production	15. Machine buffer zones	0: Isolated machines with buffer zones 1: No buffer zones
8. Degree of technology specialisation	0: All purpose technology 1: Single product family 2: Single product type	16. Sequential dependency of workers	0: None 1: Exists
		17. Hand tool manufacture	0: Other products are manufactured 1: Only hand tools are manufactured

The phylogeny of this clade is presented dendrogrammatically in figure 5.7. With industrialisation, competition increased and companies had to focus solely on hand-tools in order to manage profitability (character state (CS) 17-1). The now extinct *Industrial Factories* of the *Industrial Revolution factories* sub-division were typically large and produced a wide range of make-to-stock tools. Middle management and rudimentary industrial engineering was introduced, although most factories were still largely disorganised and resembled a maze.

Figure 5.7. A dendrogram of the phylogeny of the industrial factories division (adapted from Leseure, 1998)



The *Post-Industrial Revolution Factories* were characterised by increasing efficiency and control of production with the rationalisation and fixed routing of production (CS 1-1). Attempts to change the focus of production were also evident, and became a mixture of both make-to-stock and make-to-order (CS 5-1). Two families of factories emerged from this sub-division, termed the *Polyvalent* and *Specialist Factories.* The Polyvalent Factories Family included two species, namely *Scale Producers I* and *Market Oriented Producers.* Both species had a purely functional layout with resources organised by process centres (character 9-1), although a varied product base was still maintained (CS 14-1). The Market Oriented Producers were distinguished from Scale Producers I as they limited production to a single trade (CS 7-1) and worked in cells (CS 9-2).

The family of *Specialist Factories* includes two tribes, two sub-tribes and five species. The Specialist Factories are characterised by a unique product route (CS 2-1), a functional micro-layout consisting of inner process centres (CS 4-1) that are highly specialised (CS 8-1), the concentrated production of a single family of products (CS 12-1), a product-based macro-layout (CS 3-1), the optimisation of the flow of products (CS 15-1), and limited process diversity (CS 6-1).

The Specialist Factories then evolved down two main routes, one that focused on processes, the other on products. Two species emerged from the *Process Specialist Factories*, namely *Focused Plants* and the *Scale Producers II*. What distinguishes the two species is that the Scale Producers II reduced their operations to a single activity or a unique process (CS 11-1).

Two sub-tribes of the *Product Specialist Factories* may be discerned, labelled the *Niche Specialists* and the *Multi-Unit Factories*. The Niche Specialists' sub-tribe consists of a single species termed the *Niche Producers*, which are characterised by the restriction of productivity to a single product type (CS 8-2), with only medium sized batches (CS 13-1), and by developing specialist manufacturing knowledge and technology (CS 7-2).

The last two species to consider are from the sub-tribe of Multi-Unit Factories. The sub-tribe is characterised by the production of several family products, by micro product lines (CS 4-2) with independent parallel production lines (CS 2-2), and a sequential dependency of workers (CS 16-1). The *Scale Producers III* are distinguished from *Modern Factories* by more flexible product routing (CS 1-2), linked parallel lines (CS 2-3) and by elimination of joint process centres (CS 10-1).

Lescure (1998; 2000) argues that the construction of the cladogram of the hand-tool industry 'provides information on the key strategic decisions faced by hand-tool manufacturers' (Leseure, 1998: 239). One strategic route elaborated on was flexibility and the strategic directions that five of the eight species could take. Leseure (2000) following on from Saurez, Cusumano and Fine (1995), considered four dimensions of flexibility concerning product mix, new products, volume and delivery time.

Both the Scale Producers I and the Market-Oriented Producers, because of their large product variety, would benefit from investments in product mix flexibility. A re-configuration of the manufacturing system is required whereby diverse processes in different sequences are enabled. Leseure (2000) recommends that group technologies, manufacturing cells, flexible equipment, multi-machine handling and autonomous teams would achieve the aim of product mix flexibility. These technologies would also help achieve some level of new product flexibility providing the means to introduce new products at low cost. The disadvantage of product mix flexibility is that it hampers volume and delivery time flexibility. Therefore, these manufacturers need a stable demand pattern to satisfy volume production. An investment in a make or buy decision-making programme may also be of benefit.

As both the Focused Plants and Niche Producers are both highly specialised in one or a few products, investments in volume and delivery time flexibility would be an ideal method of increasing competitive advantage. Contemporary practices such as time-based competition, knowledge and innovation management, and total quality management could increase flexibility in both these areas. From the cladistic analysis, it was also identified that Modern Factories could also benefit from volume and delivery-time flexibility but using different technology to those recommended for the previous two species. Tools, derived from the automotive manufacturers employing lean production principles, may be of benefit here (Leseure, 2000). These may include capacity management, line balancing, set-up time reduction, and mixed model production.

In contrast, flexibility is not an issue for the Scale Producers II as any move towards a flexible system would mean, on the one hand, being less competitive with similar species, on the basis of the production of large volume of standard tools, and on the other hand, competing with more established species such as Modern Factories. It is, however, recommended that they move more towards a strategy of 'lean mass production' (Leseure, 2000). This would involve, perhaps, full integration of its operations, including resource planning systems and integrated supply chain management, a programme of mass customisation to achieve market differentiation, and some 'lean' concepts such as cost reduction and inventory reduction.

From this discussion, the usefulness of manufacturing cladistics can be seen. As structural organisations are mapped out, organisations are able to identify their position as well as their competitors. In addition, struggling manufacturers have a blueprint with which to guide organisational transformations and to achieve best practice. It also gives an indication of potential strategic directions (Leseure, 2000).

5.2.5. Automotive Assembly Plants

McCarthy et al's (1997: 272) paper provided an illustrative example (see figure 5.8 and table 5.6) of the automotive assembly plant cladogram to 'introduce the reader to the mechanics and benefits of producing a cladistic classification' (see also Leseure, 1998). The data for this research came from a number of sources including International Motor Vehicle Program (cited in Womack, Jones & Roos, 1990), historical accounts and information from car manufacturers.

Figure 5.8. A cladogram of automotive assembly plants (from McCarthy et al, 1997)

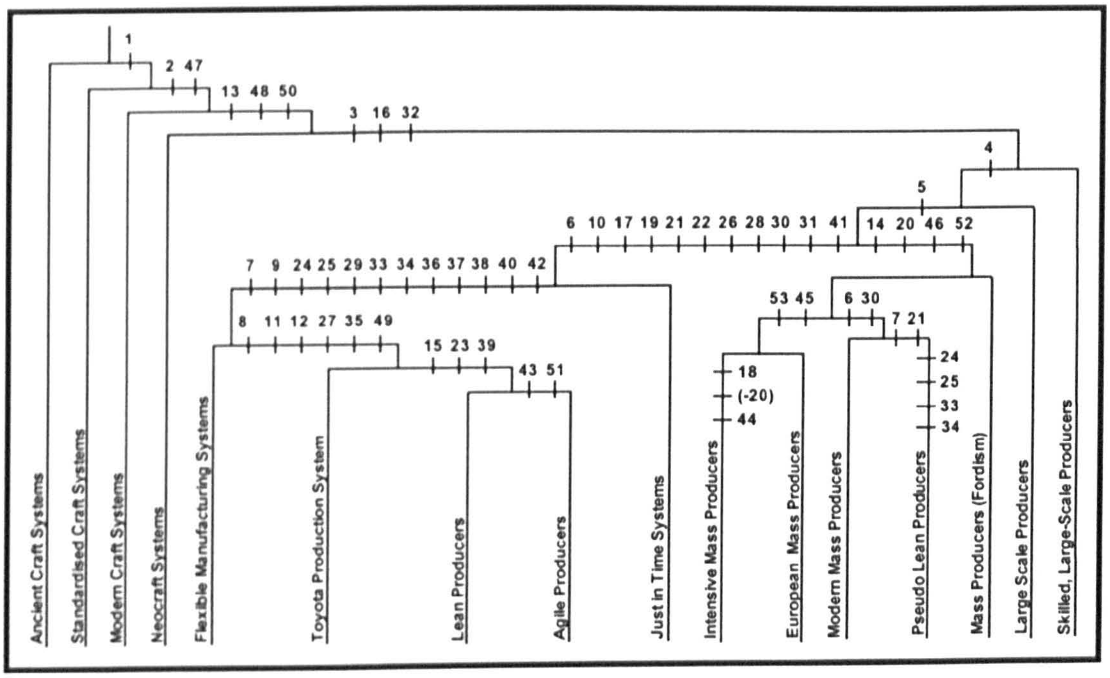


Table 5.6. Characteristics of automotive assembly plants (from McCarthy et al, 1997)

1. Standardisation of parts
2. Assembly time standards
3. Assembly line layout
4. Reduction of craft skills
5. Automation (machine paced shop)
6. Pull production system
7. Reduction of lot size
8. Pull procurement
9. Operator based machine maintenance
10. Quality circles
11. Employee innovation prizes
12. Job rotation
13. Large volume production
14. Suppliers selected primarily on price
15. Exchange of workers with suppliers
16. Socialisation training (master/apprentice learning)
17. Proactive training programs
18. Product range reduction
19. Automation
20. Multiple sub-contracting
21. Quality systems (tools, procedures, ISO9000)
22. Quality philosophy (TQM, way of working, culture)
23. Open book policy with suppliers; sharing of cost
24. Flexible multi-functional workforce
25. Set-up time reduction
26. Kaizen change management
27. TQM sourcing; suppliers selected on basis of quality
28. 100% inspection/sampling
29. U-shape layout
30. Preventive maintenance
31. Individual error correction; products are not re-routed to a special fixing station
32. Sequential dependency of workers
33. Line balancing
34. Team policy (motivation, pay and autonomy for team)
35. Toyota verification of assembly line (TVAL)
36. Groups vs teams
37. Job enrichment
38. Manufacturing cells'
39. Concurrent engineering
40. ABC costing
41. Excess capacity
42. Flexible automation for product versions
43. Agile automation for different products
44. Insourcing
45. Immigrant workforce
46. Dedicated automation
47. Division of labour
48. Employees are system tools and simply operate machines
49. Employees are system developers; if motivated and managed they can solve problems and create value
50. Product focus
51. Parallel processing
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity
53. Further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible

The *Ancient Craft Shops* of the 1880s consisted of highly skilled workers who produced unique customised cars. The first major innovation, the standardisation of parts (CS 1), was introduced by Henry Ford and resulted in the species *Standardised Craft Systems*. However, this soon evolved into the *Modern Craft System* with the introduction of assembly time standards (CS 2) and a division of labour (CS 47).

The next evolutionary step to the *Neo-Craft Systems*, also initiated by Ford, was characterised by pursuing a large volume of production (CS 13) to achieve economies of scale, to treat employees as system tools that simply operate machinery (CS 48), and to focus more on the product (CS 50). As a tighter control over the layout of the assembly line (CS 3) began making an impact as well as explicit master-apprentice training (CS 16), and with a system where one worker is dependent on the previous worker (CS 32), the *Skilled, Large Scale Producers* emerged.

A similar species, the *Large Scale Producers*, evolved as it became evident that if systems were introduced that reduced the skill requirements of the workers (CS 4) then cars could be manufactured a lot cheaper. Shortly after this, automation with machine-paced shops (CS 5) began to increase in importance and is a dominant characteristic of all other species that evolved. In the cladogram, it can be seen that there is a major point of bifurcation, with many character states involved, leading to two families – the *mass producers* and the *lean producers*.

The classical *Mass Producer (Fordism)*, named after Ford, introduced more dedicated automation (CS 46), had used many subcontractors (CS 20) that were selected purely on price (CS 14), and introduced middle management with the consequence of an increasing dependence on rules and procedures (CS 52). Two sets of two species then branch from the classical mass producer.

Down one branch are located the *Modern Mass Producer* and the *Pseudo Lean Producer*. Both species have pull production systems (CS 6) and employ preventive maintenance (CS 30), but what distinguishes the Pseudo Lean Producer is a reduced lot size (CS 7), a quality system in place (CS 21), a flexible and more multi-functional workforce (CS 24), a focus on the reduction of set-up times of the machinery (CS 25), a line balancing procedure (CS 33) where workers from one line help on another line to help time pressures, and an emphasis on teamwork (CS 34).

The species of the other branch, the *European Mass Producers* and the *Intensive Mass Producers*, exhibit none of the eight characteristics just mentioned, but both share the emphasis of a further intensification (CS 53) of immigrant labour (CS 45). In contrast to the European Mass Producer, the Intensive Mass Producer also exhibits a reduction in the product range (CS 18) and utilises insourcing (CS 44). Unlike all other mass producers, the Intensive Mass Producer attempts not to have multiple subcontractors (CS –20).

There are five species identified on the evolutionary branch to leaner production. All the following species share all of the characteristics of the *Just in Time Systems* and include the implementation of the pull production system (CS 6), specialised 'autonomation' (CS 19) along with preventive maintenance (CS 30). Also dominant in these species are quality systems (CS 21), quality circles (CS 10), and an overall quality philosophy (CS 22). In line with the quality emphasis, everything is inspected (CS 28) and errors are corrected there and then (CS 31) instead of being sent to a special fixing station, which helps reduce excess capacity (CS 41). The concept of Kaizen change management (CS 26), where step-by step improvements are always sought, is also implemented.

There are several differentiating characteristics, that define *Flexible Manufacturing Systems*, and which the next three species share. The main characteristic is the implementation of flexible automation (CS 42), which in consequence reduces both the set-up times of the machinery (CS 25) and the lot size (CS 7) required for operations. There is also an emphasis on teamwork (CS 34; CS 36) and job enrichment (CS 37) to create a flexible multi-functional workforce that can help balance the line (CS 33) when needed. The factory layout changes with an emphasis on a U-shape layout (CS 29) organised in cells (CS 38). ABC costing is also employed (CS 40).

The *Toyota Production System* also incorporates pull procurement planning (CS 8) selected on the principle of total quality management (CS 27) to complement the pull production system in place. The workers are also emphasised and seen as system developers (CS 49), jobs are rotated (CS 12) and employee innovation prizes (CS 11) are given. This manufacturing system also introduced the 'Toyota Verification of Assembly Line' (CS 35), which is a motion study procedure that takes into account repetitiveness and physical strain for job rotation planning.

Both the *Lean Producer* and the *Agile Producer*, evolved from this species. Both species added concurrent engineering (CS 39), which is a concerted collaboration between design and manufacturing departments. The species also concentrated on improving their ties with the suppliers through exchanging workers (CS 15) and keeping an 'open book policy' (CS 23) where costs and profits are shared. Agile Producers, as their name suggests, invested in agile automation for different products (CS 43) and performed processes in parallel (CS 51).

5.3. Further Research

One area for potential research is a feasibility study examining the actual applicability of manufacturing cladistics in industrial settings. Although manufacturing cladistics as an academic subject began about ten years ago it hasn't as yet been used as a tool for re-engineering. The feasibility study would need to collect and analyse data, firstly on general variables of the organisation such as age, size, and turnover, which may be used as dependent variables to investigate potential differences. Then questions need to be asked concerning, for example, whether companies would use manufacturing cladistics as a tool for organisational transformations, what problems would be possibly encountered, what aspects of the organisation would be inhibited and whether competitive advantage could be gained through the approach. Data collection would have to incorporate at least two methods – questionnaires to gauge general opinions and interviews for more in-depth analysis.

A second area of further research would be to combine cladistics with other classification schemes. Functional classification is a relatively new field of research in ecology, restricted mainly to plant ecology and as such is also an untested and novel direction in manufacturing and industry and at a time when the discipline of industrial ecology is thriving.

When applied to manufacturing, functional classification would focus on organisational processes (e.g. replication, recombination, learning and entrepreneurship) and events (e.g. birth, death, transformation and speciation). There is also a potential for cladistics to be coupled with functional studies that seek to ascertain an overall measure for complexity, stress resistance and mortality index in an industrial ecosystem.

A functional study of organisations would aim to both forecast environmental/market changes and on which manufacturing species will dominate, compete and survive such conditions. In terms of industry, stresses could constitute the lack of skilled labour, capital, materials, and machinery while disturbances could be interpreted as such happenings as fire, power disruptions, labour disruptions, and market problems (McCarthy et al, 2000).

In most of the manufacturing/management literature, the most studied functional type is typically the competitor (McCarthy et al, 2000). The potential benefits of studying the other two types (stress tolerators and ruderalists) could be many. The benefits would not only be for the industrialists involved but also for planning and policy-making. It may also benefit local economies, particularly those that are relying on mature industries where indexes of disturbance but particularly stress are significantly high. This model may also be of benefit when assessing economic conditions when concerned with new business start-up.

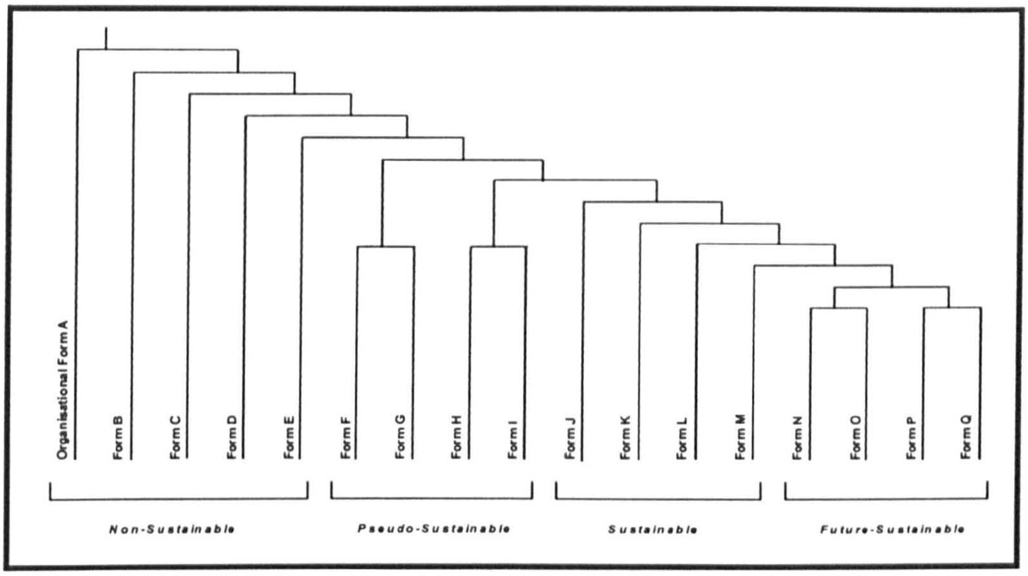
A third suggested direction for further research, which was the original aim of this thesis, is to investigate the evolutionary history of sustainable organisations. The research would have to identify, through the literature, interviews and questionnaires, and then analyse characteristics that define non-sustainable through to pseudo-sustainable (end-of-pipe mentality) to sustainable (reduce at source) organisational forms (see table 5.7).

Table 5.7. Potential sustainability characteristics (from van Berkel, Willems & Lafleur, 1997)

Inventory Tools	Improvement Tools	Prioritisation Tools	Management Tools
1. Life cycle inventory 2. Abridged LCI 3. MET Matrix 4. Eco-Balance 5. Material & energy balance 6. Process flow chart	7. Ecological principles 8. Product improvement approaches 9. Product improvement matrix 10. Pollution prevention techniques 11. Pollution prevention strategy 12. Option inventory 13. Blueprint	14. Benchmarks 15. Total cost calculation 16. Life cycle cost calculation 17. Life cycle evaluation 18. Eco portfolio analysis 19. Product summary matrices 20. Eco opportunity 21. Option evaluation	22. Design for environment 23. Cleaner production indicators 24. Process audit 25. Cleaner production guide 26. ISO14000 27. EU Eco-Management systems

The next stage would be to construct the cladograms (conceptual and then full cladograms) describing the evolution of the sustainable manufacturing (see figure 5.9 for a hypothetical cladogram). At this stage, the cladogram would offer manufacturers a benchmark of past, current and best practice. Organisations would be able to identify the position on the cladogram of both themselves and their competitors and use it as a guide in organisational re-engineering for sustainability.

Figure 5.9. A hypothetical cladogram of the evolution of sustainable manufacturing



A final suggested direction for further research, and one that is taken in this thesis, is to synthesise manufacturing cladistics with evolutionary systems modelling. As seen throughout the review, manufacturing cladistics has a serious limitation. For example, the typical cladogram only describes what forms have existed to a point in time. That is, it is essentially a description of the past. Although this would be useful for an organisation that is struggling to compete, it is in effect useless for world-class manufacturers. To elaborate, if you were a world-class manufacturer and market leader, there is no point looking at other, inferior operational structures – you are the best currently available.

One potential way to solve this problem is to synthesise manufacturing cladistics with evolutionary systems modelling, which has been developed by Allen (e.g. 1976; Allen & Ebeling, 1983; Allen et al, 1985; 1997) during the last three decades. Evolutionary systems' modelling has its roots in the pure sciences (physics and chemistry) and has a mathematical basis. A full review of this literature is conducted in the next chapter.

5.4. Chapter Conclusions

There are several important conclusions to be drawn from this literature review of classification schemes and their application to manufacturing organisations. There are several conclusions to be drawn from section 5.1 dealing with biological taxonomy. Firstly, research in this area is the most advanced to be found anywhere most of which have incorporated numerical taxonomy – the process of forming groups of taxonomic units based on character similarities and differences discerned through numerical and statistical techniques.

Numerical taxonomy increases objectivity, efficiency and discrimination between groups through its quantitative nature. It also enables the re-evaluation and re-examination of the underlying theories and principles from which the classification is constructed. Biological classification can be divided into three main groups a) phenetics, which focuses on physical similarity whilst ignoring evolution, and from the phylogenetic school of thought, b) cladistics, which has evolution as an external reference point, and c) evolutionary classifications, which attempts to synthesise the latter two approaches.

From these three schools, there is now a consensus that cladistics is the more favourable approach and as such the most appropriate technique for classifying manufacturing organisations. However, functional classifications are gaining momentum and may also prove to be fruitful when considering manufacturing classifications. Functional studies are essentially based on the species' function in the ecosystem or, in other words, their strategies for survival.

Section 5.2 reviewed the application of cladistics to manufacturing classifications. It was argued that if a cladogram was comprehensively constructed it would provide not only a benchmarking system but also a tool with which to guide manufacturers contemplating organisational re-engineering. Recent research in manufacturing cladistics has been applied to the complexity of manufacturing organisations, to management styles, the hand-tool industry, and the automotive industry. These applications are also a good indicator of the success of the cladistic approach when applied to manufacturing.

After reviewing the work to date, further research areas were identified (section 5.3). As no manufacturer has actually utilised this technique, it was concluded that a feasibility study was needed in order to identify the problems of adoption in industry. Three additional areas of research were also identified and involve: a) the synthesis of cladistics with functional classification schemes; b) the cladistic evolution of sustainable manufacturing (the original research aim); and, c) the synthesis of manufacturing cladistics with evolutionary systems modelling (the new research aim for the thesis). The first synthesis, involving the integration of cladistics and functional studies, appears to be fruitful. In this scheme, form and function would be united. In other words, a species' (biological or manufacturing) physical attributes as well as their strategy for survival would be the basis of this classification scheme.

The latter synthesis would enable simulations of the evolution of manufacturing forms, to identify other potential organisations, to explore decisions, and as a guide for more competitive organisational transformations. Manufacturing cladistics essentially depicts history and is only really useful for organisations struggling to survive. This combined approach, however, would also be useful for world-class manufacturers as potential superior structures may emerge in the simulations.

CHAPTER 6 – EVOLUTIONARY SYSTEMS

6. Introduction

For more then twenty-five years, Peter Allen has been developing a theoretical contribution concerning evolution and evolutionary processes that may be applied to all complex systems. The work presented here traces its origins back to the insights expressed in Prigogine's (1973) Nobel Prize winning research. The original research aim was to develop a cladistic history of sustainable manufacturing. However, as discussed in this chapter, a more fruitful research direction was found. In addition to developing cladograms, evolutionary systems modelling also has the potential to simulate the evolutionary processes involved in any complex system. This chapter also presents an alternative, but complimentary, perspective to the reviews of complex systems and the models developed in chapters 3 and 4, and builds on many of the principles discussed.

Much of the foundation for Allen's thinking was evident in his first publication on the subject (e.g. Allen, 1976). Since then, his perspective of evolutionary systems has gained much substance, depth and numerous applications. Continuing on from Prigogine, Allen applied this thinking to problems and issues confronting ecology. From this platform, it was obvious that the processes underlied all complex systems of an evolutionary nature, and Allen attempted to prove this point by applying his model to problems in geography and economics (among others).

Along the way, embellishments and refinements were made including the assumptions that are made to reduce complexity to simplicity, the notion of 'evolutionary drive' and the 'Law of Excess Diversity'. By applying this framework, anything that evolves may be modelled and as such one further research direction is identified and discussed.

6.1. Evolution and the Problem of Modelling

As Allen (1982; 1984) pointed out, many models are concerned with firstly understanding but then predicting and planning for the evolution of a system. Indeed it is generally thought that the ability to predict the future state of a system is a prerequisite of understanding. Therefore, modellers are typically concerned with the questions (e.g. Allen, 1984: 29) 'is the future already contained in the present or is it, on the contrary, for us to create?'

Through the classification and identification of system components as well as the causal links and underlying mechanisms, fundamental laws of nature were elicited (the Newtonian mechanical model) and ultimately the inevitability of the future behaviour of the system. Therefore, the answers to modellers' questions seem to have been answered and most of the social sciences embraced this thinking.

However, new thinking and work on systems that can exchange energy and matter across their boundaries, as described in chapters 3 and 4, has shown this to be flawed. Although Newtonian models are correct for isolated systems that inevitably reach thermodynamic equilibrium, they are inappropriate when considering the activity of nature and social systems, the evolution of which pushes the system further from equilibrium. This is not to say that mechanical models are defunct, they are just inappropriate for evolutionary systems.

Another problem is that modellers are typically trying to find the most optimal state that the system can take. If we can reduce reality to a machine, then we are able to determine whether certain modifications result in the system being faster, use less energy, materials, requires less labour and skill and, more often than not, able to save money. This is an overt point in the discussions and philosophy of both sustainability and industrial ecology (chapter 2) and to some extent manufacturing cladistics (chapter 5). Models of both sustainability and IE are not so much predictive models but are overt attempts to optimise the system towards sustainability without any real thought of evolution. This is not to say that optimisation is altogether erroneous, but that it represents only one side of the evolutionary story.

Optimisation (and only optimisation) has particularly been seen in research involving (to name but a few):

- Urban systems and how to plan a growing city, transportation routes, and the placing of industry

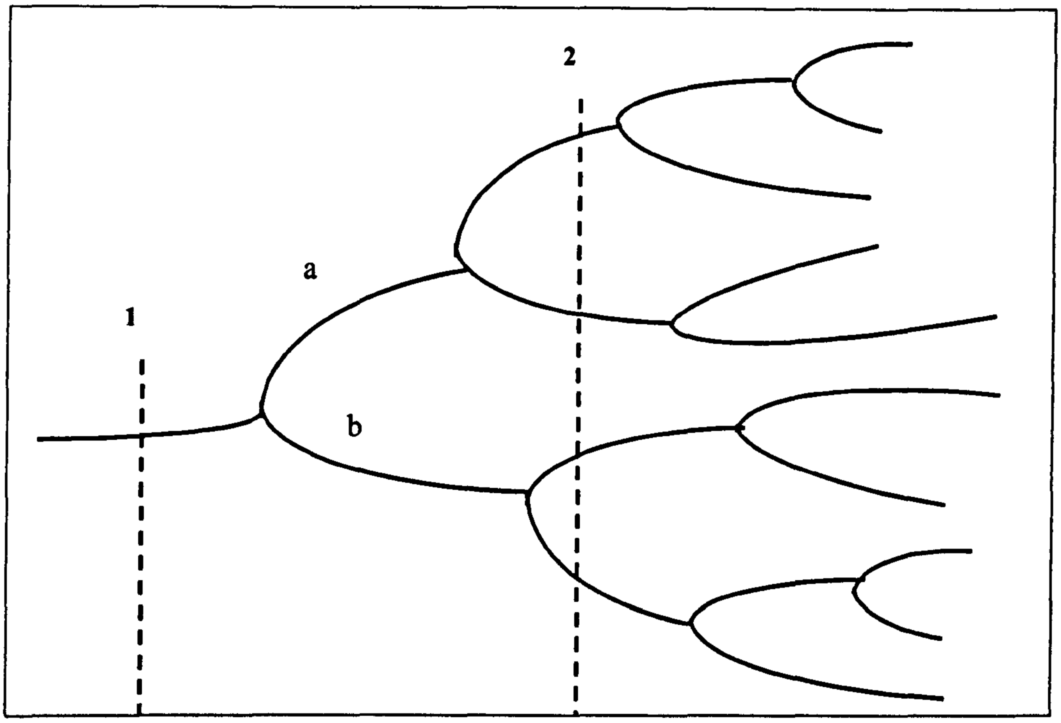
- Economics and how, for example, to reach a perfect equilibrium state between supply and demand and the prediction of stock prices
- Company structure and how, for example, each firm can reach world-class status (see manufacturing cladistics discussed in chapter 5)
- Industrial systems and how, for example, a perfect equilibrium and match between inputs and outputs can be achieved, with energy usage and waste generation minimised.

All models are a reduced description of what is actually there. The modeller attempts to take everything out that is superfluous and leave in only the essential elements. The most often result is a mechanical model. Most mathematical models, however, also represent change over time. This point is important, because the change that is usually contained in the model is of a quantitative nature.

Qualitative change, such as structural change, adaptive responses and learning within, is not usually represented. This is a huge problem when studying evolution, as qualitative change is an inherent characteristic. When qualitative change takes place in a system, typically the model needs to be at least calibrated, and at worst re-designed.

Evolution is a subtle partnership of chance and determinism and the future not wholly inevitable (Allen, Engelen & Sanglier, 1984). The roles of both chance and determinism can be seen in figure 6.1. When the system is at point 1, far from bifurcation, the system is deterministic, in as much as fluctuations from non-average behaviours do not perturb the average course. Average behaviours dominate and the process of optimisation prevails. This is somewhat representative of the notion of incremental evolution. Most descriptive models and mechanistic models are very often appropriate at these times.

Figure 6.1. A system's evolutionary tree: chance and determinism (from Allen, 1984)



Chance plays a crucial role however, when the system, close to bifurcation, becomes unstable and may decide the next trajectory. Indeed, average behaviour (the substance of typical models) plays no role in choosing a branch; it is the non-average or eccentric behaviours, the variations around the average that lead the 'decision' (Allen, 1984). This is more representative to the idea of punctuated equilibria, that is, if Gould and Eldridge's (1977) notion of equilibrium is ignored. Once change has occurred, the average is redefined and optimisation begins again.

At point 2 the system may have taken on one of four completely different qualitative states. This sheds light on the issue and difference of prediction and post-diction. With hindsight it is easy to see how, and to some extent why change occurred, but looking to the future it may be one of many eccentricities that shapes the direction taken. Another important feature of evolutionary systems concerns the solutions derived. Although the equations are quantitative, the solutions (the different branches that may be taken) are qualitatively different (Allen et al, 1984). The causation or explanation is paradoxically circular (Allen, 1984). The learning is from within the system and models that truly represent evolutionary processes need to incorporate this.

Origami, the art of paper folding, demonstrates perfectly many of the points Allen (1984; Allen et al, 1984) is making. By taking a flat piece of paper and making a series of folds, many configurations, reflecting familiar objects or animals, may be created. Of particular importance when considering evolutionary complex systems, is that with each fold, new traits, characteristics or concepts emerge. With origami it may be wings, legs, petals and even elegance. Different folds represent different branches on the tree that are qualitatively different. Importantly, choosing the 'best' end state is based on a value judgement, which in natural evolution is based on its 'fit' in, or compatibility with the enveloping environment.

At certain points bifurcations take place separating the past from the present and restrict evolution, through irreversible folds, to certain future pathways. Historically, modelling has typically described structure reflecting what the system is now. The description does not incorporate the past (particularly the alternative branches) or the future and as such is incapable of exploring its evolution. Reductionism would describe the colour, weight and dimensions of the paper and not the emergent forms. Traditional science cannot cope with this problem, if another fold were to happen, for example, the modeller would have to adjust his/her model – only the present is considered, the system's past and future are always disregarded.

An analogy may also be made (e.g. Allen, 1984) in that the patterns of the folds represent DNA and the configuration defined as the number of folds needed to create it. The separating folds could then determine the relationship or difference between objects, establishing common ancestors. With this, however, the order of folds, i.e. the dynamics, would be required, highlighting the significance of the system's history. Without the actual order of the folds, the final object could take on countless possible configurations, many of which would be ambiguous and unrecognisable.

6.2. Modelling Assumptions

According to Allen (1992; 1998a; 1998b; 2001a), in the past, systems have been modelled with certain underlying assumptions most of which reduce the utility of the model. Allen (1992; 1997) points out that there is a corresponding hierarchy of models, where stronger assumptions reduce the complex reality, where there are no assumptions, to increasing simplicity of understanding. Common assumptions in modelling are:

1. That a boundary exists between the system and environment
2. That objects are classified resulting in a taxonomy of components
3. That the components of the system are homogeneous, have diversity normally distributed around the mean and do not change
4. That the collective or overall behaviour of the system results from smoothed, average processes
5. That the system moves to or is already at a stationary or equilibrium state. It is assumed that the relationships between variables are fixed and unchanging.

Allen (1998a; 1998b; 2001c) argues that the following four models relate directly to the number of simplifying assumptions made. If all five assumptions are justified the result is an equilibrium model. Although extremely simple, the model appears to enable perfect long-term prediction and complete understanding and knowledge. The values of every variable and their interactions are precisely known. So, for example, in these types of models the outcome of a particular decision or action is known beforehand. In short, equilibrium models are essentially only a descriptive approach applied in post-hoc situations. Despite the known limitations of equilibrium models they are still used today to deal with problems in economics, spatial geography and in environmental science (Allen, 1998a; 1998b; 2001b).

When making the first four assumptions but not equilibrium, the result is a mechanical model that corresponds to non-linear dynamics. However, with assumption 4, that all interactions and events are of an average type, the direction or trajectory of the system is smooth, deterministic and perfectly predictable and is the most probable path. This implies perfect determinism, and that the 'actors' within the system have in fact no way of changing the course of events.

Models that make only the first three simplifying assumptions are self-organising dynamic models. By not making the assumption that all interactions are average, systems are able to spontaneously re-configure spatially/organisationally. Good or bad luck are captured in these descriptions. Chance fluctuations at particular points in time, particularly instabilities, are crucial and may lead to positive feedback that in turn may lead to qualitatively different spatial regimes. These systems are able to change to environmental conditions. This is incorporated in the mathematics as 'noise'. With self-organising models, instead of having only one possible trajectory and dynamic regime to investigate, all possible trajectories are investigated and these can lead to different possible attractors. This therefore changes the purpose of the model from predictive to more exploratory.

According to Allen (1998a; 1998b; 2001d) what distinguishes self-organisational processes from evolutionary processes is the internal variability in the components themselves. Whereas with self-organising systems there are diverse interactions between individual components only, evolutionary systems assume internal diversity of the individual components and that the components and sub-components co-evolve. That is, the individual components have the ability to innovate, mutate or learn through their experiences. This corresponds to the individuality of people or species. For example, with reproduction, genetic information is never passed on perfectly. Successive progeny makes sure that pure conditions are never replicated. Behaviour 'space' or potential behaviours are continually explored. But different behaviours may be neutral, successful or unsuccessful in the system and may be selected for or against. Through positive feedback, successful behaviours are amplified while unsuccessful ones are suppressed.

6.3. Applications

Evolutionary systems modelling has now been applied successfully to several disciplines including ecology, urban studies, economics, fisheries, crime rates, and design. For the purpose of this chapter however, the first three research areas will be highlighted, as they are the most relevant to this thesis (and future research directions).

6.3.1. Ecology

One of Allen's first papers on evolutionary complex systems was published in 1976 and developed a mathematical expression describing the invasion of new behaviours into a system. The work is important, however, as previous (and later) attempts have only addressed the issue of predator-prey interactions until some steady state or limit cycle behaviour is reached, for example, the Volterra-Lotka systems and the Evolutionary Stable Strategies by Maynard-Smith (1982). Eigen and Schuster's (1979) work on hyper-cycles is perhaps the only exception. Apart from Allen, however, no one has addressed either the invasion of mutant or innovative behaviours causing instabilities in the system or the conditions in which an invasion is successful – in short, this paper considered the *actual effects* of evolution on an ecosystem.

The research presented in the paper represents a theoretical application of Prigogine's 'order through fluctuation', where biological evolution through selection surrounds the diffusion and proliferation of mutant behaviours determined by their success, or relative performance, in birth and death rates. Birth and death rates represent, for example, competition for resources, mating success, avoiding/catching prey, and rearing offspring.

Allen points out that in terms of stability considerations mutation or speciation has a very small probability when compared to the normal processes of births and deaths and, as a source of fluctuation, must be decoupled from the average population dynamics. Before the mutation can be considered in the average density description (i.e. the number of individuals in the populations taken from their success in the birth and death rate processes) the new behaviour must develop a significant influence in the ecosystem, i.e. reach a certain value in the stability equations that corresponds to the new behaviour's performance with respect to others in the system. Once a mutant is successful, instability occurs, the system re-organises, structurally and qualitatively, and evolution continues. If the behaviour doesn't reach this critical value, that is, if the new mutant has poorer birth and death rates, it will be selected against and will eventually disappear from the system.

This is best described through the use of a real-world example – that of a predator-prey system. If a prey is considered, then a successful mutant must either have a better average performance than a competing species (i.e. in an existing niche) or have the ability to exploit a new niche. With the former case, the new mutant must have, for example, a better ability to find food or rear its young, or of avoiding predation, and if so ultimately replaces the old behaviour. With the latter, the diversity of behaviours in the ecosystem is increased and the available energy, through the vital materials within each niche, is increased and exploited. A corresponding condition for a mutant predator to be successful in this system is also given. The condition for a mutant predator is either that it is better, on average, at catching the prey and/or at avoiding fatalities. The mutant species, therefore, can only be successful if the effectiveness of each population on average is increased.

Thus, any evolutionary history concerns successive invasions of both prey and predator that are able to invade. This means that with evolution over time the available energy through vital materials is increased as new niches are exploited. The ability of the prey species to survive and rear offspring increases and the predator's death rate decreases. This means that over a long period of time, the facility or mechanism in which the predator catches prey, that is, the interaction rate of the prey being eaten and predators eating (and the conversion into predator biomass), remains constant overall. This means that the facility increases for the predator and decreases for the prey. This is an important finding as it describes perfectly the armaments race often seen in predator-prey systems where one often counters successive moves of the other. One important conclusion from Allen's theory is that the consumer/producer ratio steadily increases as evolution proceeds. In other words, biomass is steadily passed on from the producer populations up the consumer chain. The criterion of evolution presented, therefore predicts the long-term trends in such systems.

In support of this conclusion, Allen points to two types of ecosystems – one natural and one 'artificial' (or man-made). Firstly, surveys of the populations of oceanic producers, phytoplankton, is, in the majority of cases, only as large as the consuming populations that depend on it. Although phytoplankton are extremely effective, this is not passed on fully to its own population but onto the consumers. Oceanic ecosystems are the most representative of this phenomenon, as the environment is largely unchanging allowing this trend to fully develop. With agriculture, the 'artificial' example, man has had to intervene in order to pass on the benefits of the producer population. Without any intervention and with humankind's ingenuity that has improved both hunting and gathering facilities, and the ability to avoid predation, the prey population, which mankind depends on, would diminish, severely restricting, if not extinguishing both. That is, the genetic countermeasures of the producers, is far too slow, when compared to the socio-cultural evolution of humankind. Agriculture is humankind's intervention, where the prey's birth-rate as well as the vital materials with which the prey depend on, are artificially increased, leading to humankind's (the consumer) population explosion.

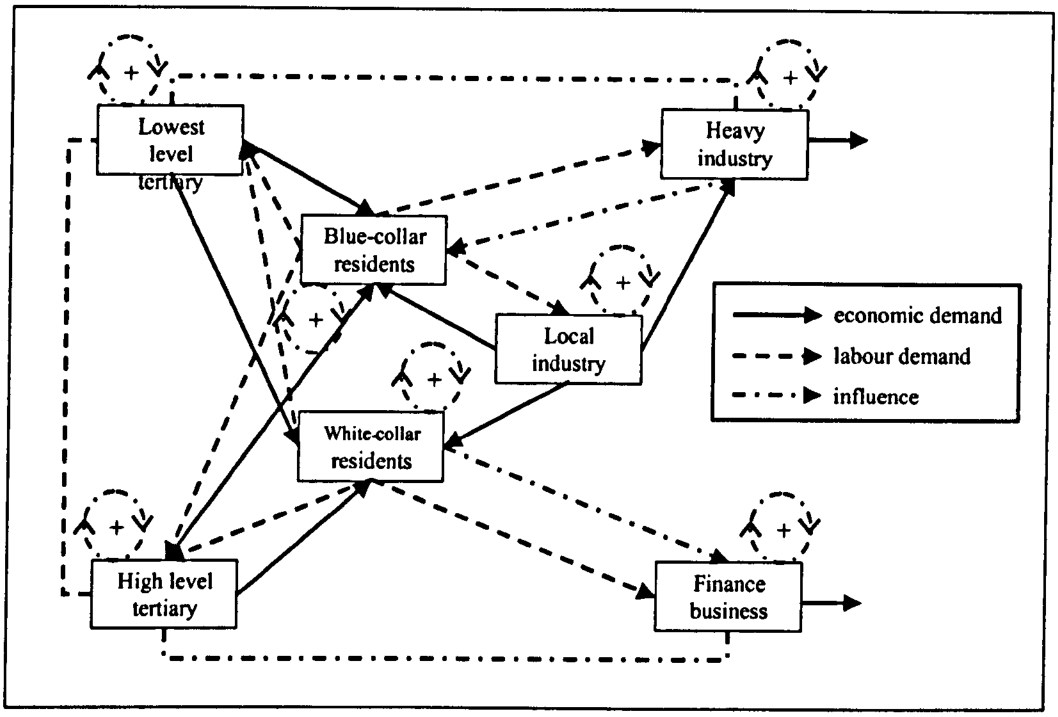
6.3.2. Urban Systems

Beginning in 1978 (e.g. Allen, 1978; Allen & Sanglier, 1978; 1979a; 1979b; 1981; Allen, 1982; 1984; Allen et al, 1984; Allen et al, 1985), evolutionary systems theory began to be applied to urban systems and their evolution. The models were based on urban actors, their dynamic interaction and their drive to survive through both cooperative and competitive activities. One particular model with a loose resemblance to the city of Brussels, which will be reviewed here in detail, consisted of five different employment types with residents belonging to two different socio-economic groups (i.e. white- and blue-collar workers). Each model variable is represented in the model by locational densities, with each actor having different preferential criteria depending on their role in society (Allen, 1984). The employment types are as follows:

1. Heavy industry
2. Light industry
3. Exporting tertiary
4. Infrequent specialised tertiary
5. Elementary tertiary.

The scheme for the criteria for the actors settling in a particular location can be seen in figure 6.2. To elaborate, external demand provides jobs, the actors are attracted to jobs and locate near the employment, and the residents create more jobs through further economic demand, and vice-versa. The system begins to structure due to two main reasons. The first reason is due to the interaction scheme (see figure 6.2), which contains non-linear mechanisms creating fluctuations and instabilities. The evolution of residents, of jobs and of densities is described by these mechanisms. Although it is possible to have a homogeneous spatial distribution, i.e. an equal number of actors at each location, the solution is very unstable. Any fluctuations by the actors (different strategy), will inevitably lead to success driving the system to an uneven spatial distribution with areas of high and low populations (Allen, 1984).

Figure 6.2. The urban-multiplier for a simplified model of a city (from Allen et al, 1984)



The second reason is due to the geography and the networks for transportation. In this particular model there are two networks. Locations and the accessibility of the networks are incorporated into the model. One network represents a road system (private network) with three qualities of roads. The other is a public transportation network and incorporates trains, buses, trams and a metro system. This dynamic transportation system leads to multiple consequences of particular decisions (Allen et al, 1985).

The simulations led to very interesting observations. After one evolutionary run, equating to 40-50 years real time, the city evolves to a structure of concentrations that are highly interdependent. Heavy industry organises into to distinct concentrations with blue-collar workers distributed close-by. At first, light industry has a diffuse distribution but then begins to concentrate and, at the end of the simulation, settles more or less exclusively in the north east of the city. Finance and business, on the other hand, begins as a concentration in the middle of the city but then diffuses spatially until a rapid concentration and growth occurs at a point just next to the city centre. Throughout the evolution, both types of workers begin to create suburbs concentrated around the transportation networks. With sub-urbanisation, shopping centres appear and grow amplifying urban sprawl (Allen et al, 1984).

This work on the evolution of urban cities demonstrated the ability of these types of models in exploring the consequences of particular decisions. Allen et al (1984) gave several insightful examples where changes are made to either the spatial organisation or the geography (e.g. transportation network). Outcomes of the decision of introducing a new shopping centre at particular times are explored first. Firstly, an investment to the equivalent of 4000 jobs in a new shopping centre is made at approximately 15 years through the original simulation described above. The investment pays off and is successful.

Consequently, other nearby initiatives, which succeed in the original, now fail. However, if the same investment is made at the same location again but at approximately 30 years, the venture fails and completely vanishes from the urban space. When the investment was increased to the equivalent of 5000 jobs, it again succeeds. Similarly, if the investment remains the same (4000 jobs) but the location chosen is elsewhere, the venture again succeeds.

The model may also be used to explore both short- and long-term consequences due to changes in the transportation network. In this example, a new metro line is added across the city. As the evolution proceeds the blue-collar workers begin to migrate to each terminal. This is in contrast to the white-collar workers who migrate to the city centre creating a degree of gentrification. Similar explorations could shed light on the costs and benefits of certain routes of certain types (e.g. bus, tram and metro routes), the frequency of use and the degree of upheaval of the populace involved.

External interventions and their impact on urban living could also be explored. Natural disasters such as earthquakes, hurricanes and floods, as well as human interventions such as war or acts of terrorism, and their potential effects could be explored. Allen et al (1984) demonstrated this point with a less dramatic example - introducing a line of hills at the beginning of the simulation that divides the city. The line of hills replaces the main transportation route in the previous simulation. This reduces the functionality of heavy industry as accessibility is reduced, which in previous simulations benefited from the good transport. The city that evolves is completely different with heavy industry, and as a consequence light industry and the blue-collar workers, located diffusely throughout the city. The white-collar workers, instead of being located in the southeast as in previous simulations, settle along the line of hills. Importantly, the whole city is stunted as the line of hills significantly lessens the global economic attractivity. This is represented mainly in increases in travel costs associated with work and leisure.

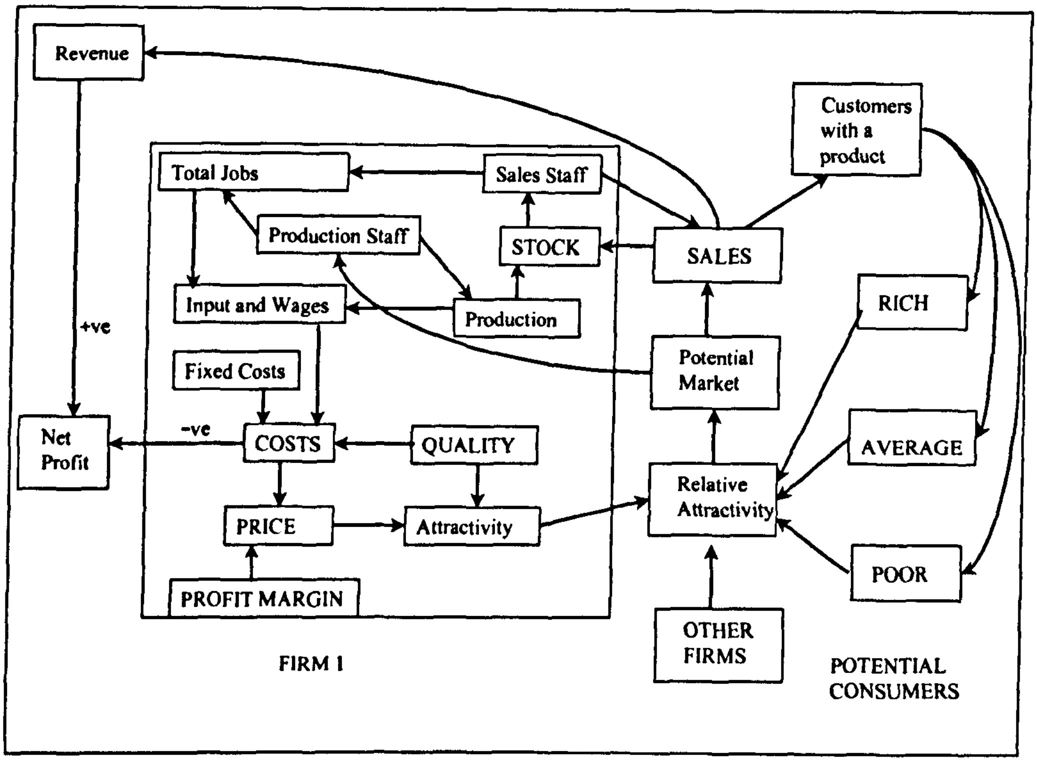
In a final example, Allen et al (1984) explored increased investments in telecommunication and computing systems. This has a huge impact on the central business district with many office jobs beginning to appear outside the core until at a critical point in time the central business district disappears. This also has major ramifications on transportation network patterns, residential locations and the location of retail centres.

To conclude this application of evolutionary systems modelling to urban systems, many of the simulation results reported above realistically mimic activities in real urban systems. Real applications therefore can be made and the consequences of far-reaching decisions such as those affecting the location of industries and retail outlets may be explored as well as policy changes, transportation routes and even telecommunication systems.

6.3.3. Economic Models

Recently, these ideas have also been applied to economic markets and their structuring (Allen, 1992; 1998b; 2001a; 2001c). The resulting models demonstrate how economic markets self-organise through competition to form an ecology of firms producing products serving particular niches in the market. One particular self-organising model (making the first three modelling assumptions; see section 6.2), reviewed here in detail, involves three firms and their growth and decline, when attempting to produce products that differ in quality and price. Customers, differentiated by their revenue, buy products according to their tastes and their sensitivities to price. Figure 6.3 depicts the interaction scheme for the model.

Figure 6.3. The interaction scheme for the 3-firm market model (from Allen, 1998b)



According to Allen (2001a), each firm produces goods according to costs of production (materials and wages) as well as the start-up and fixed costs. The sales team then try to locate and interact with potential customers to sell the products. The mark-up on a product must cover the costs of production and staff wages whilst also making a profit to provide income for shareholders. After buying a product the customer then disappears from the market for the duration of the product lifetime. The niches of the market are differentiated by only quality and price. With higher quality, the lifetime of the product increases. There are three general types of customer – rich, average and poor and as such have different sensitivities to price (although all prefer high quality products).

Allen (1998b) presented an example of such an evolutionary run. Firm 1 has a quality of 10 (on a scale of 1-20 with 20 being the best quality) and a mark-up of 70%. Firm 2 has a quality of 7 with a mark-up of 80%. Firm 3 has a quality of 13 with a mark-up of 70%. With respect to each other, firm 2 is the most successful, growing rapidly and paying shareholder dividends of 6.08 (arbitrary) units. Firm 1 has moderate success, grows a little and pays dividends of 4.52 units. Firm 3 fails altogether. On the next run, firms 1 and 2 keep the same strategy whereas firm 3, keeping the quality of 13, reduces its mark-up to 40%. This strategy is moderately successful, and firm 3 stays in the game for the duration of 9 years paying average dividends of 2.58 units. Firm 2 still dominates having a large share of the market niche that provides for the 'poorer' customers. This time firm 1 fails after about 6 years.

After such runs the model can then be used to test out different strategies. For example, in the last run firm 1 failed after six years due to a crisis caused by the competition of firms 2 and 3. The question is whether a change in strategy would have saved firm 1. Therefore after six years, firm 1 changes the mark-up from 70% to 50%, but is again unsuccessful. The other two firms have a significant grip of the market. However, when firm 2 changes its strategy by reducing its mark-up from 80% to 40%, firms 1 and 3 become far more competitive and eliminate firm 2 altogether.

The model may also be used for longer-term explorations. In particular, strategies could be explored where shareholders have low payoffs in the short-term in order to gain significantly in the long term. Different strategies may be experimented with at any time in the simulations as demonstrated above. In addition, the effects of an increased sales force, advertising campaign, the impacts of research and development, changes in technology, and changing external conditions (e.g. legislation) may be explored.

The model may also be adapted to represent evolutionary learning by making only the first two modelling assumptions (see section 6.2). With this model instead of the modeller changing the strategies the firms themselves experiment through a trial and error process. Different qualities, mark-ups, and sales force sizes may be experimented with. The various strategies are attempted when either profits are low or when the firm fails altogether. In one example, what is interesting is that although the firms come and go quite regularly the actual market and customers are served very well.

When running the model again but with different initial conditions, an altogether different result is obtained. This time firms 2 and 3 do extremely well with high mark-ups. Firm 1 fails initially and thereafter struggles to compete. However, the market is poorly served this time with only a few expensive products sold. Even after 50 years only half the potential market, representing the rich and some average customers, is exploited. The situation is reinforced as high mark-ups cause low sales, which in turn makes it necessary to have high mark-ups. However, after 50 years firm 3, after responding to low profits, experiments with a low mark-up. This instantly causes a considerable instability forcing firms 1 and 2 to also reduce mark-up and quality. As a consequence the market nearly doubles in size and all customers are now well served.

To conclude this section on economic modelling, although the models described above are very simple and a little removed from reality, what can be gained are invaluable insights into the learning mechanisms of entrepreneurs and of the evolution of firm resilience and adaptability. Evolutionary systems may be used to simulate the consequences of various strategies of, for example, differing mark-ups, qualities and sales force size. The dimensions of products in these examples only relate to quality, whereas the product's quality differ in many respects and may include performance, weight, size, style, colour, and efficiency. The model can easily be adapted to incorporate all of these qualities and can quite easily be used for real companies.

6.4. The Law of Excess Diversity

While working with the above applications and in trying to tackle the broader issues of sustainability (and similarly resilience, flexibility and adaptability) Allen (2001a) proposed the *Law of Excess Diversity* in an attempt to articulate the most important theme running throughout evolutionary systems thinking. The Law of Excess Diversity follows on and extends Ashby's (1960) thinking on systems that are self-regulating and adaptable. Ashby introduced the *Law of Requisite Variety* that stated that if a system with N states was to adapt successfully then it needed at least N possible internal states in its repertoire. In short, variety can only help overcome variety.

However, Ashby's (1960) view related more to systems that had a good degree of determinism. Allen's law however, accepts uncertainty, the limits to knowledge, the fact that the future is unknown and that change is inevitable. Uncertainty and change not only occurs in the external environment but also from within the system. The Law of Excess Diversity therefore states that (Allen, 2001a: 176):

> For a system to survive as a coherent entity over the medium and long term, it must have a number of internal states greater than those considered requisite to deal with the outside world.

Whereas 'variety' relates to potential outcomes that have attributes that are shared, 'diversity' relates to possibilities that have different attributes, i.e. belong to different qualitative states. The law translates the meaning of an adaptable system in that there is either hidden diversity or contains mechanisms with which to produce diversity. Allen (2001b) also distinguishes between diversity and micro-diversity. In terms of the modelling assumptions (see section 6.2) diversity is associated with self-organising systems where the interactions between components are of a non-average nature and thus diverse.

The evolutionary systems perspective, however, takes into account the non-average behaviours inherent in the components and sub-components – the internal- or micro-diversity. It is this micro-diversity that creates real evolutionary change. Furthermore, the explorations and probing of the micro-diversity through error making processes cannot be controlled at the level of the system, but in terms of their relative performance in their local situation. Allen (2001a) deliberately refers to the process as error making so as to highlight the degree of chance involved and the openness of the process. Components with their own individuality as well as the imperfect transfer of information creates a forum for learning and evolution. This process has also been referred to as 'evolutionary drive' (Allen & McGlade, 1986; 1987).

6.5. Further Research

Through the application of evolutionary systems methodology, as can be seen throughout the discussion in this chapter, the evolution of anything that can evolve, e.g. biological species, ecosystems, and social systems, may be simulated if data were available. One particular area of further research is the combination of evolutionary systems modelling techniques and manufacturing cladistics. This is taken further, empirically investigated and reported on in the next three chapters.

6.5.1. Evolutionary Systems Modelling and Manufacturing Cladistics

In terms of the advantages of manufacturing cladistics to manufacturers a) best practice can be benchmarked (McCarthy, 1995b), b) change and transformations may be guided (McCarthy et al, 1997), and c) strategies maybe developed as problem areas can be identified through the cladogram (Leseure, 2000). However, there are limitations. The cladogram is essentially a description of the past and is of no use to world-class manufacturers who can only compare with inferior organisations. It also says nothing about the 'losers' (those organisations that didn't survive for one reason or another), which is perhaps an important omission. Learning from past mistakes could prevent future disaster. Furthermore, the cladogram gives no insight, with the exception of post-hoc analyses, into many of the problems confronting management decision-makers.

By combining manufacturing cladistics and evolutionary systems modelling, cladograms may be constructed that include not only past and present organisations but also organisations that *could* have evolved or that may evolve in the future. In reality we have one evolutionary 'run' and 'what ifs?' are fleeting wishes. With computer simulations, evolutionary runs are limitless and there is always the potential for something better that has as yet not evolved for one reason (possibly chance) or another (e.g. decisions). In theory, the data that would be needed are the opinions of experts of how the characteristics, used to define organisational structure, interact with each other. If all the interactions between characters are collected, through, for example, questionnaires and interviews with experts, then limitless evolutionary 'runs' of manufacturing organisations may be simulated. In industry, characteristics may include 'standardisation of parts', 'assembly time standards' and 'division of labour'.

The potential advantages of this approach are several. For example, if a world-class manufacturer contemplating a major organisational transformation could conduct a thorough exploration of the pros and cons of crucial and even not-so-crucial decisions. Decisions may be explored time and again in, for example, different contexts or with the presence or absence of other important variables.

Another advantage would be if an organisation developed a new characteristic of its own, e.g. a new plant layout, but were unsure of the consequences of adopting it, then the model could be applied to reduce uncertainty and to some extent the risk associated with change. This approach could explore many possible outcomes of the adoption. For instance, problem characters could be identified and investigated or different scenarios could be run. Furthermore, potential barriers to introducing new technologies and practices could be identified beforehand and discussed and planned for in more detail.

The original research aim, highlighted in chapter 5, was to develop cladograms describing the evolutionary history of sustainable manufacturing. However, with this chapter in mind, a new research aim was devised – to integrate manufacturing cladistics and evolutionary systems modelling, enabling simulations of the actual evolutionary history. Ideally, research would be conducted firstly into developing a cladogram of the evolution of sustainable manufacturing and then gather the data of the interactions between the characteristics identified so that simulations could be performed of the evolutionary processes involved in sustainable manufacturing.

As can be seen from the discussion, this research using the evolutionary framework may provide a useful decision-making aid for manufacturers in their bid to become more sustainable. Through the identification of sustainability characteristics, such as life cycle analysis, waste minimisation and energy efficiency schemes, and the synthesis with more traditional characteristics, such as different production systems, factory layouts, and levels of automation, it would be possible to explore problems of technology transfer, potential consequences in all areas of organisation, and new sustainable structural solutions.

The research would have to identify, analyse and weight characteristics that define non-sustainable through to pseudo-sustainable (end-of-pipe mentality) to sustainable (reduce at source) organisational forms. The next stage would be to construct the cladogram describing the evolution of the sustainable manufacturing. At this stage, the cladogram would offer manufacturers a benchmark of past, current and best practice. Organisations would be able to identify the position on the cladogram of both themselves and their competitors and use it as a guide in organisational re-engineering for sustainability.

To develop the evolutionary model of sustainable manufacturing the research would have to establish, through sources such as questionnaires and interviews with industrial and academic experts, participating company records and archives, how the sustainability characteristics interact with traditional manufacturing characteristics such as those, for example, that make-up lean production. Through computer simulation, it would then be possible to explore their interactions, as with this study, but in addition between sustainability characteristics and traditional characteristics.

This research would help examine opportunities and barriers to new practices, techniques and technologies that could increase the sustainability of the manufacturing system. In addition, it would also be possible to explore how market conditions, internal organisational structures and practices, government policies and calculations of risk might influence the adoption of sustainable technology. From this, and from a knowledge of the internal structures of participating companies, guidance can be given that will influence evolution in the direction of increased sustainability.

However, as this constitutes the combination of two large research projects, and with limitations in both time and resources in mind, it was decided that a compromise had to be taken. In addition, as the integration of manufacturing cladistics and evolutionary systems modelling had not yet been attempted there was the additional risk of failure. Therefore it was decided that a pilot study was needed to assess the feasibility of the synthesis. The case study chosen was the manufacturing cladistics research on the automotive industry reviewed in chapter 5. Chapter 7, which describes the methodology, discusses the reasons behind this decision in more detail.

6.6. Conclusions

There are several important conclusions to be made after reviewing the literature concerning evolutionary systems thinking. The first concerns modelling and the different types of models now available. This highlighted that the more evolution is accurately modelled the less the model is capable of predicting. However, the real underlying evolutionary processes give modellers a deeper insight into the system under study. Instead of prediction, different possible future states may be explored which, when used with this understanding and with the right intentions, provide modellers with the ability to reduce uncertainty and risk and to glimpse possible future states of the system. Modelling assumptions, which increasingly reduce complexity to simplicity and the potential of the model from predictive to explorative, correspond to vastly different types of models, namely equilibrium, dynamic, self-organising and evolutionary models.

From the first application in 1976 to the evolution of an ecosystem, evolutionary systems modelling has been successfully applied to several very different areas and disciplines including urban and economic systems (reviewed here) as well as fishery management, crime rates, design, climate change, and new product development. All applications demonstrate the ability of the model to realistically represent the evolutionary nature of the system and the ability to explore different strategies, decisions and policies.

One main area for further research has been identified and concerns the combination of two complimentary, but currently unrelated, areas of inquiry – that of evolutionary systems modelling and manufacturing cladistics. By applying the evolutionary framework, not only can the past be represented (as with manufacturing cladistics) but also the future possibilities of manufacturing organisations and their structure. This research is carried out and reported on in the next three chapters.

CHAPTER 7 – MODELLING MANUFACTURING EVOLUTION: METHODOLOGY

7. Introduction

This chapter presents the methodology behind a collaborative project between the author and Professor Peter Allen from the Complex Systems Management Centre, Cranfield University, whose work was reviewed in chapter 6. The chapter begins by describing firstly the method behind the data collection process, then a description of the model and finally the aims and objectives of the investigation are presented.

The main aim was to address the problems that may be encountered in the introduction of new and sustainable technologies, practices and policies. However, as outlined in section 6.5 (chapter 6) sustainability characteristics were not investigated per se, nonetheless, many similar problems had arisen. The main problem studied was the consequences of introducing new practices and technologies, and the decisions behind these introductions.

The synthesis was therefore based on the manufacturing cladistics research on the automotive industry reviewed in chapter 5. There were several reasons behind this decision. The first reason was because the evolution of the automotive industry is well known and publicised through both academic and trade publications. The factory layout, worker organisation and the practices employed are also well known with many pervasive in all manufacturing. Sustainability characteristics on the other hand are not so well known and have only been developed recently.

The second reason was that the actual cladogram of the automotive industry has already been developed and with 53 characteristics and 16 organisational forms, the data collected would prove to be rich. To investigate sustainability characteristics, a new cladogram would have be developed, which is a major research project in itself. The final reason is that the automotive cladogram has been published several times (e.g. McCarthy et al, 1997; 2000; McCarthy & Ridgway, 2000).

7.1. Questionnaire Methodology

There are two aspects of the methodology – the data collection procedure and the simulation model. As this was an altogether new investigative approach, the methodology was of an exploratory nature rather than an established one. The aim of the research was not to apply the findings but to determine if the approach had a potential viability for application, in short, to see whether the data collected actually worked with the model and if similar findings were found to that in the study of the automotive industry.

With hindsight the methodology had several minor flaws that will be highlighted in chapter 9. Therefore, it must be emphasised that this investigation was more of an exploration of methodology than of application. Nonetheless, several fundamental observations were still elicited and the potential for application demonstrated.

7.1.1. *Apparatus*

The apparatus used for this research included a company list acquired through Yell.com, a covering letter for participating manufacturers introducing and describing the research, a questionnaire divided into four parts, envelopes, a computer, Microsoft Excel for basic data analysis and the evolutionary systems model which was ran in the Microsoft Dos® operating system and programmed in Turbo Basic®.

7.1.2. *Questionnaire Design*

The design of the questionnaire was lengthy and proceeded through three pilot stages where consecutive amendments were made. The objective of the questionnaire was to gauge the opinions of the manufacturers of how the characteristics of the automotive industry (see table 7.1) interacted on one another.

Table 7.1. Characteristics of automotive assembly plants (from McCarthy et al, 1997)

1. Standardisation of parts
2. Assembly time standards
3. Assembly line layout
4. Reduction of craft skills
5. Automation (machine paced shop)
6. Pull production system
7. Reduction of lot size
8. Pull procurement
9. Operator based machine maintenance
10. Quality circles
11. Employee innovation prizes
12. Job rotation
13. Large volume production
14. Suppliers selected primarily on price
15. Exchange of workers with suppliers
16. Socialisation training (master/apprentice learning)
17. Proactive training programs
18. Product range reduction
19. Autonomation
20. Multiple sub-contracting
21. Quality systems (tools, procedures, ISO9000)
22. Quality philosophy (TQM, way of working, culture)
23. Open book policy with suppliers; sharing of cost
24. Flexible multi-functional workforce
25. Set-up time reduction
26. Kaizen change management
27. TQM sourcing; suppliers selected on basis of quality
28. 100% inspection/sampling
29. U-shape layout
30. Preventive maintenance
31. Individual error correction; products are not re-routed to a special fixing station
32. Sequential dependency of workers
33. Line balancing
34. Team policy (motivation, pay and autonomy for team)
35. Toyota verification of assembly line (TVAL)
36. Groups vs teams
37. Job enrichment
38. Manufacturing cells'
39. Concurrent engineering
40. ABC costing
41. Excess capacity
42. Flexible automation for product versions
43. Agile automation for different products
44. Insourcing
45. Immigrant workforce
46. Dedicated automation
47. Division of labour
48. Employees are system tools and simply operate machines
49. Employees are system developers; if motivated and managed they can solve problems and create value
50. Product focus
51. Parallel processing
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity
53. Further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible

In the first pilot stage the answer options were based on a seven-point Likert scale with three negative choices (-3 to -1), one neutral (0), and three positive choices (1 to 3). The design enabled the gauging of the dual interaction of characteristics, that is, for example, characteristic A's influence on characteristic B and vice versa, which in some instances may be different. If respondents were unsure of the answer (i.e. unsure of either the one or both the characteristics or their interaction) they had the option of entering a '9'. The questionnaire thus consisted of a 53x52 matrix with a total of 2,756 responses.

The questionnaire was given to 3 relevant academics and 2 industrialists and feedback was obtained. Although all pilot respondents attempted the questionnaire not one questionnaire was completed. Feedback from the respondents indicated that it was far too long to complete. With this in mind two amendments were made. The first amendment concerned the answer options, which were reduced to a three-point scale – negative, neutral and positive. The option of '9', for unsure answers, was again included. The second amendment concerned the matrix, which was consequently halved. This meant that only a measure for the combined interactivity of the characteristics in terms of overall productivity was given. That is, the question that was asked was whether both characteristics together had either a negative, neutral or positive effect on productivity. The questionnaire therefore consisted of a 53x52/2 matrix with a total of 1,378 responses. The questionnaire was again given to the pilot respondents. Again all respondents attempted the questionnaire but only one completed the matrix. The total time taken to complete the form was 3.5 hours, which was again far too long a time in which to receive an adequate return rate.

The questionnaire was therefore divided into four parts (A, B, C and D). The number of responses was thus reduced to between 325 and 351 depending on which part of the questionnaire was to be filled out. This time the answer options remained the same as before. Each part was then given to four pilot respondents (from the previous pilot phases). The pilot respondents completed the questionnaire in a time between 35 and 50 minutes. The feedback from the respondents in this pilot phase was on the whole positive. Therefore the questionnaire was deemed to be appropriate for the manufacturing organisations. Refer to appendix 2 for sample covering letter and questionnaire parts.

7.1.3. *Procedure*

Before a description of the procedure is given, it is important to state that the ideal respondents should be personnel involved in automotive manufacture. However, the first ten automotive manufacturers in UK that were contacted did not show any interest and were unwilling to participate in the research. This led to the decision that a change in sampling was required to that of all manufacturers whatever the sector. This is justified somewhat, as many of the practices, technologies and manufacturing systems detailed in McCarthy et al's (1997) research are common in all manufacturing, and if not common at least well known. This has important implications, however, for the integrity of the findings and conclusions particularly concerning the original research by McCarthy et al (1997), which must be taken tentatively.

Having made the decision that the sample would be drawn from general manufacturing sectors, the procedure went through a number of phases. The first phase was to obtain a list of manufacturing organisations through Yell.com. Each organisation was then telephoned to determine whether: (a) they were in fact manufacturers; (b) they had over 25 employees; (c) who the most appropriate respondent would be; and, (d) the name and position of the most appropriate respondent. The second phase was concerned with the design of the questionnaire and pilot stages (described above). When the final draft of the questionnaire was completed, the whole package (the covering letter, the questionnaire, the return-addressed envelope, and outgoing envelope) was personalised as much as possible. This encompassed writing by hand the potential respondents name on the covering letter as well as a signature. The address on the outgoing envelope was also handwritten. The respondents were also offered the final research paper as an incentive. The final questionnaire was sent by post to 1,565 manufacturing organisations throughout most of the UK (England, Wales and Scotland). Table 7.2 details the different manufacturing sectors and the number of companies representing that sector that the questionnaire was sent to.

Table 7.2. The different manufacturing sectors that the questionnaires were sent

Manufacturing Sector	SIC Code	Total Companies	Manufacturing Sector	SIC Code	Total Companies
Leisure and General Goods	3550	1	Textiles - General Products	17541	5
Footwear and Leather Goods	1920	4	Metal Products	2743	4
Metal Products	2914	29	Footwear and Leather Goods	18249	1
Textiles - General Products	2875	5	Sound and Lighting	3150	78
Footwear and Leather Goods	1920	5	Security Equipment	2863	14
Electric Components and Equipment	2734	12	Industrial Equipment and Machinery	33202	4
Textiles - General Products	2875	7	Tools	2940	3
Electric Components and Equipment	3130	7	Industrial Equipment and Machinery	2940	20
Packaging	2040	3	Metal Products	2875	5
Packaging	2872	16	Measuring and Control Instruments	33202	3
Leisure and General Goods	2953	25	Medical Goods	3310	43
Office and Computer Equipment	3001	4	Measuring and Control Instruments	33201	6
Medical Goods	33401	4	Leisure and General Goods	36509	3
Measuring and Control Instruments	32202	29	Leisure and General Goods	3630	5
Metal Products	2861	3	Textiles - General Products	1752	5
Measuring and Control Instruments	33201	11	Office and Computer Equipment	3001	19
Tools	2940	6	Packaging	21219	37
Electric Components and Equipment	3110	17	Packaging	2040	24
Electric Components and Equipment	3210	105	Measuring and Control Instruments	3350	2
Electric Consumer Goods	2971	33	Leisure and General Goods	33403	7
Electric Components and Equipment	2971	8	Leisure and General Goods	2464	6
Measuring and Control Instruments	33201	6	Tools	2940	5
Electric Components and Equipment	3120	35	Measuring and Control Instruments	33202	3
Electric Components and Equipment	2940	1	Electric Components and Equipment	3210	45
Textiles - Knitwear and Materials	1722	25	Electric Consumer Goods	5143	21
Electric Consumer Goods	2923	11	Packaging	2951	5
Textiles - General Products	5170	8	Industrial Equipment and Machinery	2811	2
Textiles - Knitwear and Materials	17549	2	Tools	2862	5
Textiles - Knitwear and Materials	1722	15	Industrial Equipment and Machinery	36639	9
Textiles - Knitwear and Materials	17402	6	Industrial Equipment and Machinery	2913	5
Measuring and Control Instruments	33202	4	Textiles - General Products	1711	5
Precision Goods and Equipment	3350	18	Metal Working	3622	1
Footwear and Leather Goods	2954	1	Leisure and General Goods	2861	9
Electric Consumer Goods	3230	4	Medical Goods	33401	41
Electric Components and Equipment	3110	29	Metal Products	2851	2
Electric Components and Equipment	3162	14	Footwear and Leather Goods	1930	2
Electric Components and Equipment	3130	33	Metal Products	2875	2
Electric Components and Equipment	3140	19	Leisure and General Goods	3640	24
Tools	2940	45	Metal Products	2812	3
Textiles - General Products	1771	54	Medical Goods	3310	7
Textiles - General Products	17511	38	Leisure and General Goods	2861	5
Footwear and Leather Goods	17549	4	Metal Products	2821	3
Textiles - General Products	1725	106	Measuring and Control Instruments	33201	14
Footwear and Leather Goods	1920	8	Electric Consumer Goods	3230	11
Footwear and Leather Goods	1930	45	Packaging	2872	1
Measuring and Control Instruments	3310	2	Tools	2940	6
Electric Consumer Goods	3230	16	Tools	2862	2
Metal Products	2751	3	Tools	2940	25
Textiles - Knitwear and Materials	1771	5	Packaging	21219	6
Textiles - General Products	17549	20	Electric Consumer Goods	2971	5
Publishing	2222	23	Measuring and Control Instruments	2924	1
Leisure and General Goods	36509	17	Textiles - General Products	1722	12
Measuring and Control Instruments	33201	14	Textiles - Knitwear and Materials	1711	12
Packaging	2956	7		Total:-	1565

The covering letter was addressed to the managing director, manufacturing manager, operations manager, or a person of a similar status pre-determined by telephone. Of the 1,565 questionnaires, 73 were returned equating to just less than an expected 5% return rate (table 7.3 lists the return questionnaires from the manufacturing sectors with their respective SIC codes). In terms of questionnaire parts, the following were received:

- 27 questionnaires from part A
- 15 questionnaires from part B
- 16 questionnaires from part C
- 15 questionnaires from part D.

Table 7.3. The manufacturing sectors that the questionnaires were returned from

Manufacturing Sector	SIC Code	Manufacturing Sector	SIC Code	Manufacturing Sector	SIC Code
Textiles - General Products	1725	Office and Computer Equipment	3001	Medical Goods	3310
Textiles - General Products	1725	Office and Computer Equipment	3001	Leisure and General Goods	3640
Textiles - General Products	1752	Electric Components and Equipment	3120	Leisure and General Goods	3640
Textiles - General Products	1752	Electric Components and Equipment	3120	Leisure and General Goods	3640
Textiles - General Products	1771	Electric Components and Equipment	3120	Electric Consumer Goods	5143
Footwear and Leather Goods	1920	Electric Components and Equipment	3130	Textiles - General Products	17511
Footwear and Leather Goods	1930	Electric Components and Equipment	3140	Textiles - General Products	17549
Publishing	2222	Sound and Lighting	3150	Textiles - General Products	17549
Leisure and General Goods	2464	Sound and Lighting	3150	Packaging	21219
Leisure and General Goods	2861	Sound and Lighting	3150	Packaging	21219
Packaging	2872	Sound and Lighting	3150	Packaging	21219
Metal Products	2914	Sound and Lighting	3150	Packaging	21219
Metal Products	2914	Electric Components and Equipment	3162	Measuring and Control Instruments	33201
Metal Products	2914	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Metal Products	2914	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Tools	2940	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Industrial Equipment and Machinery	2940	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Industrial Equipment and Machinery	2940	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Tools	2940	Electric Components and Equipment	3210	Measuring and Control Instruments	33201
Tools	2940	Electric Components and Equipment	3210	Industrial Equipment and Machinery	33202
Leisure and General Goods	2953	Electric Components and Equipment	3210	Measuring and Control Instruments	33202
Leisure and General Goods	2953	Electric Components and Equipment	3210	Medical Goods	33401
Leisure and General Goods	2953	Electric Consumer Goods	3230	Leisure and General Goods	33403
Electric Consumer Goods	2971	Medical Goods	3310	Leisure and General Goods	36509
Electric Consumer Goods	2971				

7.2. The Evolutionary Systems Model Methodology

The evolutionary systems model, written by Peter Allen, has been developed in Turbo Basic® and run in the Microsoft Dos® operating system (see appendix 3 for the program). It is based on the equations given in Allen (1984; 1985) and Allen et al (1985). There are numerous variables that can be manipulated and calibrated. There are four variables directly related to the running of the model that need to be explained. The first is the running time of the evolutionary model. This may be adjusted to accommodate reaching the final solution. Solutions are typically found between 10,000- and 50,000-time units.

The second variable is the number of characteristics launched in the model. This can be controlled so that specific or experimental organisational forms may be introduced and explored. The third variable is the starting value of the characteristic. Characteristics may have a value between 0-30 units. The value may be thought of as the success or importance to the organisation. In addition, if a new characteristic is launched, the starting value also indicates the commitment of the organisation to this characteristic.

An analogy can be made with an ecosystem – if an ecosystem (organisation) were defined by the constituent species (characteristics) then the value of the species would relate to their population total and hence its success and importance to the ecosystem. Most of the runs reported in the next chapter, launch the characteristics with a starting value of 5. Due to the interactions between characteristics during the evolutionary run, the characteristic value changes reflecting the overall importance of the characteristic to the organisation.

The final variable to be highlighted is the rate at which random or specific characteristics may be introduced. Character introduction reflects innovation and/or exploration. This function may be turned off all together reflecting an organisation that does innovate/explore. To get sensible results the innovation rate should be adjusted so that a degree of organisational stability is achieved before introducing the next characteristic. Typically, character introductions are between every 300 – 3000+ time units. An organisation that launches characteristics every 300-time units, for example, would be very innovative. This function may also be programmed to launch characteristics at random time intervals.

7.3. The Study's Aims and Objectives

There are several aims and objectives of the study. The first aim is to test the stability of 14 of the 16 organisational forms that make up the automotive industry. There are two methods of doing this both of which are reported. The first is to evolve the organisations as laid out and specified in the original automotive assembly plant cladogram. This entails launching the *Modern Craft System* (with Character-states (CS) 1, standardisation of parts, CS 2, assembly time standards, and CS 47, division of labour) until a stable solution is found and then launching the additional characteristics (i.e. CS 13, large volume production, CS 48, employees are system tools and simply operate machinery, and CS 50, product focus) that make up the *Neocraft System* until that configuration reaches a stable solution and so-on. The second method is to launch each organisation and their defining characteristics separately with each character-state having equal importance. The results of both methods may then be compared and contrasted.

There are several objectives of testing the stability of the organisational forms. The first is to demonstrate how the model works and the potential usefulness of this approach. The second objective is to see if the model results reflect the results of the actual cladogram. The third is to determine if there are any potential flaws in the methodology or design of the data collection procedure.

The second aim is to explore the innovation process and to see what new structures look like, when the model is left to randomly innovate, and if they resemble any organisation in the original manufacturing cladistics research. This is achieved by launching an organisational form with one characteristic and then introducing random characteristics at particular intervals for a particular evolutionary time length. The objective of this is twofold. The first is to purely explore evolutionary processes, the issues involved and potential new organisational forms. The second is to attempt to draw out some fundamental observations relating to the evolution of the automotive industry.

The final aim of this research is to launch a particular organisational form at its most stable solution, in this case the *Modern Mass Producer*, and then introduce characteristics either singularly or in combinations. There are two main objectives of this aim. The first is to relate the results to issues concerning decision-making, uncertainty and specific barriers to the introduction of new practices. The second objective is to demonstrate the exploratory capacity of the model, particularly when evolving completely new organisational structure.

CHAPTER 8 – MODELLING MANUFACTURING EVOLUTION: RESULTS

8. Introduction

This chapter reports on the results of the collaborative investigation between the author and Professor Peter Allen of the Complex Systems Management Centre, Cranfield University. The chapter is organised around five main sets of results. The first describes the simulation of the full evolutionary sequence of the organisations specified in McCarthy et al's (1997) original manufacturing cladistics research on the automotive assembly plant evolution (the procedure for these simulations is described below). This section concludes with an amended cladogram produced by the full evolutionary simulation procedure. The amended cladogram is then compared and contrasted with the original cladogram of McCarthy et al's (1997) research.

The next section of results tracks the performance of certain characteristics throughout the full evolutionary simulation run giving an alternative perspective of the evolution. The third set of results simulated the evolution of individual organisations with the characteristics all starting with the same value. The results are then compared and contrasted with both McCarthy et al's (1997) original work and the full evolutionary simulation procedure. Again an amended cladogram is developed and contrasted both with the original cladogram of McCarthy et al (1997) and with the amended cladogram produced by the full evolutionary simulation procedure.

The fourth set of results investigated the random evolution of an organisation. This entailed beginning the simulation with the Standardised Craft System (with only character-state 1, standardisation of parts) and then launching random characteristics to determine firstly whether they succeed or fail and secondly what end state is reached and whether it compares to any of the organisations in either the original manufacturing cladistics work or any of the simulated organisations. The final set of results investigated organisational transformations. This procedure simulated a particular organisation, in this instance the Modern Mass Producer, and then introduced individual or bundles of related characteristics. Three specific areas were explored – characteristics related to quality, workforce and supplier policies.

8.1. Stability of Organisational Forms: Full Evolutionary Run

Following the aims of this study, the characteristic combinations (i.e. organisational forms) as detailed by McCarthy et al (1997) were simulated. The Ancient craft system (no characteristics) and the Standardised Craft System (only one characteristic) were not simulated, as there would be no character interaction. Figure 8.1 is the original automotive assembly plant cladogram given in McCarthy et al (1997).

Figure 8.1. The automotive assembly plant cladogram (from McCarthy et al, 1997)

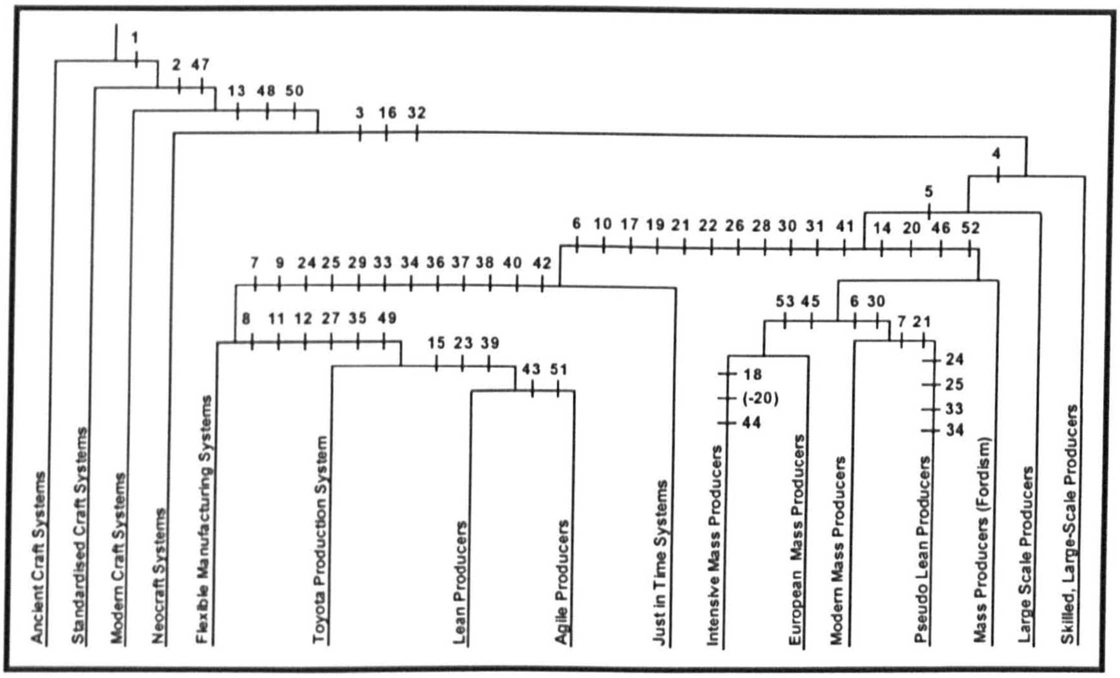


Table 8.1 lists the character-states and their associated numbers. Table 8.2 lists the 16 organisational forms and their defining characteristics. The following results are produced from what is termed a full evolutionary run. The full evolutionary run is the procedure where the values of the characteristics of the stable solution (the end of a simulation) are carried over into the next simulation. The new characteristics that distinguish the next organisational form are then introduced with a value of 5 units. The process is continued for the rest of the simulations of the organisational forms.

This is in contrast to individual simulation runs (reported in section 8.3) where all characteristics of the organisational form are launched with equal value units (i.e. 5 value units).

Table 8.1. Characteristics of automotive assembly plants (from McCarthy et al, 1997)

1. Standardisation of parts
2. Assembly time standards
3. Assembly line layout
4. Reduction of craft skills
5. Automation (machine paced shop)
6. Pull production system
7. Reduction of lot size
8. Pull procurement
9. Operator based machine maintenance
10. Quality circles
11. Employee innovation prizes
12. Job rotation
13. Large volume production
14. Suppliers selected primarily on price
15. Exchange of workers with suppliers
16. Socialisation training (master/apprentice learning)
17. Proactive training programs
18. Product range reduction
19. Autonomation
20. Multiple sub-contracting
21. Quality systems (tools, procedures, ISO9000)
22. Quality philosophy (TQM, way of working, culture)
23. Open book policy with suppliers; sharing of cost
24. Flexible multi-functional workforce
25. Set-up time reduction
26. Kaizen change management
27. TQM sourcing; suppliers selected on basis of quality
28. 100% inspection/sampling
29. U-shape layout
30. Preventive maintenance
31. Individual error correction; products are not re-routed to a special fixing station
32. Sequential dependency of workers
33. Line balancing
34. Team policy (motivation, pay and autonomy for team)
35. Toyota verification of assembly line (TVAL)
36. Groups vs teams
37. Job enrichment
38. Manufacturing cells'
39. Concurrent engineering
40. ABC costing
41. Excess capacity
42. Flexible automation for product versions
43. Agile automation for different products
44. Insourcing
45. Immigrant workforce
46. Dedicated automation
47. Division of labour
48. Employees are system tools and simply operate machines
49. Employees are system developers; if motivated and managed they can solve problems and create value
50. Product focus
51. Parallel processing
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity
53. Further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible

Table 8.2. The 16 organisational forms and their characteristics

1	Ancient Craft Systems																								
2	Standardised Craft Systems	1																							
3	Modern Craft Systems	1	2	47																					
4	Neocraft Systems	1	2	47	13	48	50																		
5	Skilled Large Scale Producers	1	2	47	13	48	50	3	16	32															
6	Large Scale Producers	1	2	47	13	48	50	3	16	32	4														
7	Mass Producers (Fordism)	1	2	47	13	48	50	3	16	32	4	5	14	20	46	52									
8	Modern Mass Producers	1	2	47	13	48	50	3	16	32	4	5	14	20	46	52	6	30							
9	Pseudo Lean Producers	1	2	47	13	48	50	3	16	32	4	5	14	20	46	52	6	30	7	21	24	25	33	34	
10	European Mass Producers	1	2	47	13	48	50	3	16	32	4	5	14	20	46	52	53	45							
11	Intensive Mass Producers	1	2	47	13	48	50	3	16	32	4	5	14	46	52	53	45	18	44						
12	Just In Time Systems	1	2	47	13	48	50	3	16	32	4	5	6	10	17	19	21	22	26	28	30	31	41		
13	Flexible Manufacturing Systems	1	2	47	13	48	50	3	16	32	4	5	6	10	17	19	21	22	26	28	30	31	41		
		7	9	24	25	29	33	34	36	37	38	40	42												
14	Toyota Production Systems	1	2	47	13	48	50	3	16	32	4	5	6	10	17	19	21	22	26	28	30	31	41		
		7	9	24	25	29	33	34	36	37	38	40	42	8	11	12	27	35	49						
15	Lean Producers	1	2	47	13	48	50	3	16	32	4	5	6	10	17	19	21	22	26	28	30	31	41		
		7	9	24	25	29	33	34	36	37	38	40	42	8	11	12	27	35	49	15	23	39			
16	Agile Producers	1	2	47	13	48	50	3	16	32	4	5	6	10	17	19	21	22	26	28	30	31			
		41	7	9	24	25	29	33	34	36	37	38	40	42	8	11	12	27	35	49	15	23	39	43	51

The first organisational form to be simulated according to the cladogram (figure 8.1) is the Modern Craft System (labelled as F3, e.g. firm 3, in the figure), as it is the first organisation in the evolution to have more than one characteristic (an essential requirement for the interaction scheme of the computer model). The Modern Craft System consists of character-states 1, standardisation of parts, 2, assembly time standards, and 47, division of labour. Each bar represents a characteristic with the character-state number indicated below the bar. The characteristics are ordered increasingly from left to right. For example, the first bar on the left represents CS 1, standardisation of parts; the second bar represents CS 2, assembly time standards and so on. The starting and end values of the three characteristics can be seen in figure 8.2. All three character-states perform particularly well with character-states 1 and 2 having an end value of 24 and with CS 47 ending with a value of 29. The success of these characteristics is likely to be due to the lack of other characteristics that may interact negatively.

Figure 8.2. Simulation of the Modern Craft System from launch (Time=0) to stable solution (Time=10,000)

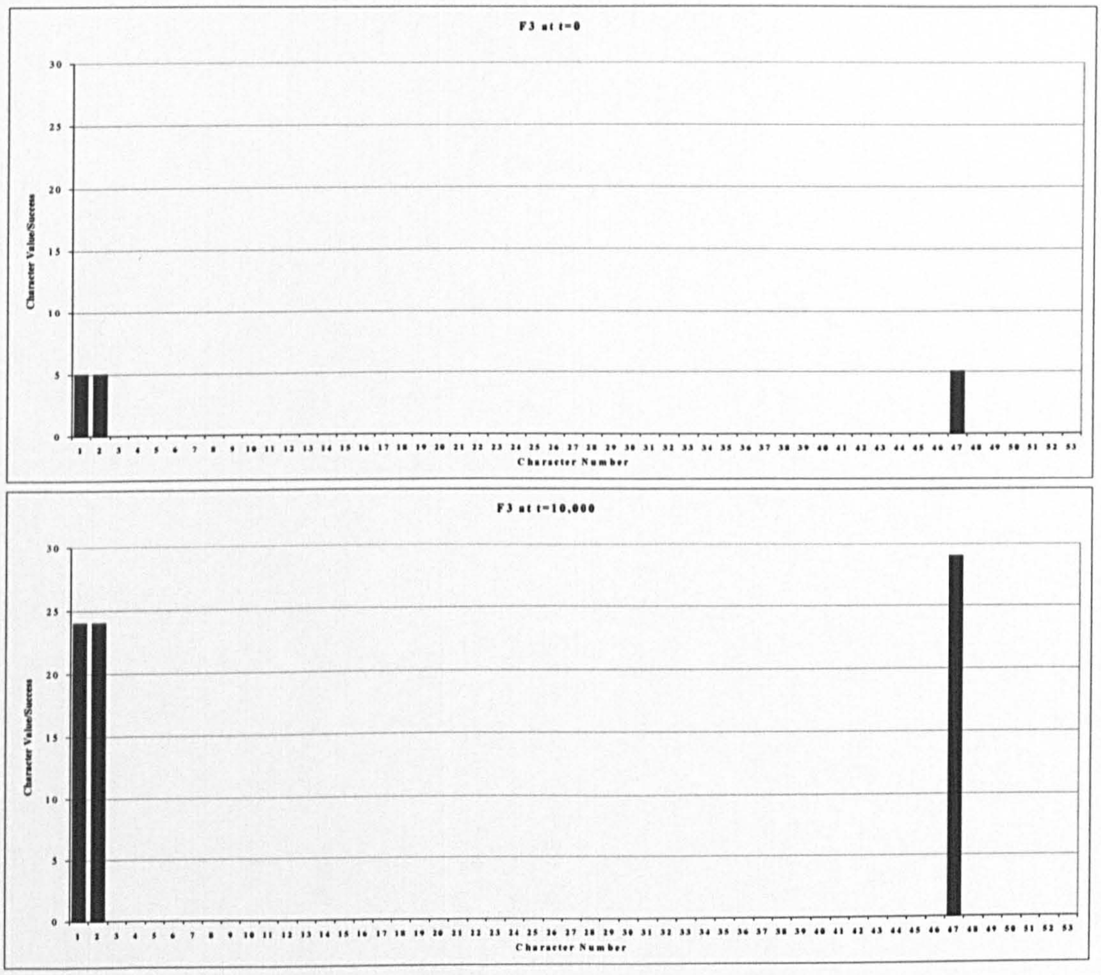
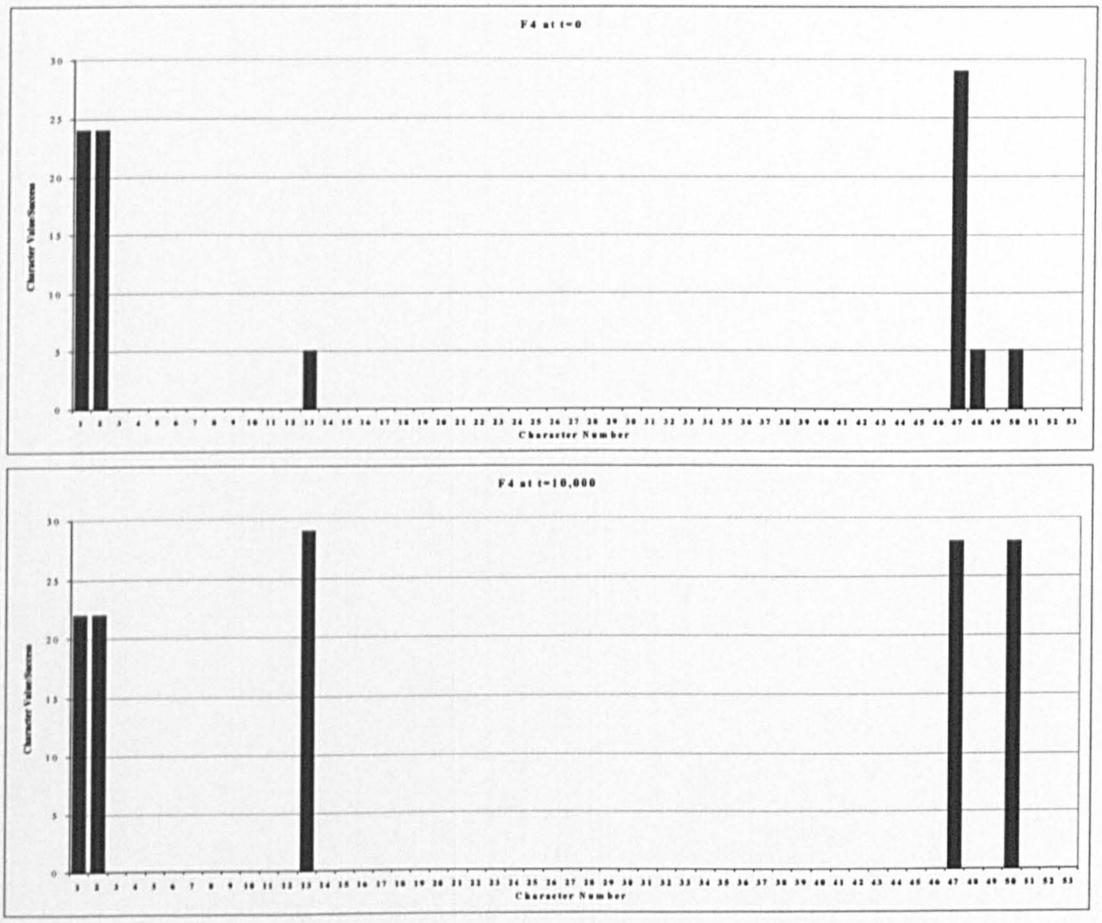


Figure 8.3 illustrates the simulated evolution of the Neocraft System (labelled as F4 in the figure). Firstly, it can be seen, according to the procedure for the full evolutionary run, that the simulation (figure 8.3 at Time=0) is launched with both the final values of the Modern Craft System (see figure 8.2) and the additional character-states (CS 13, large volume production, CS 48, employees are system tools and

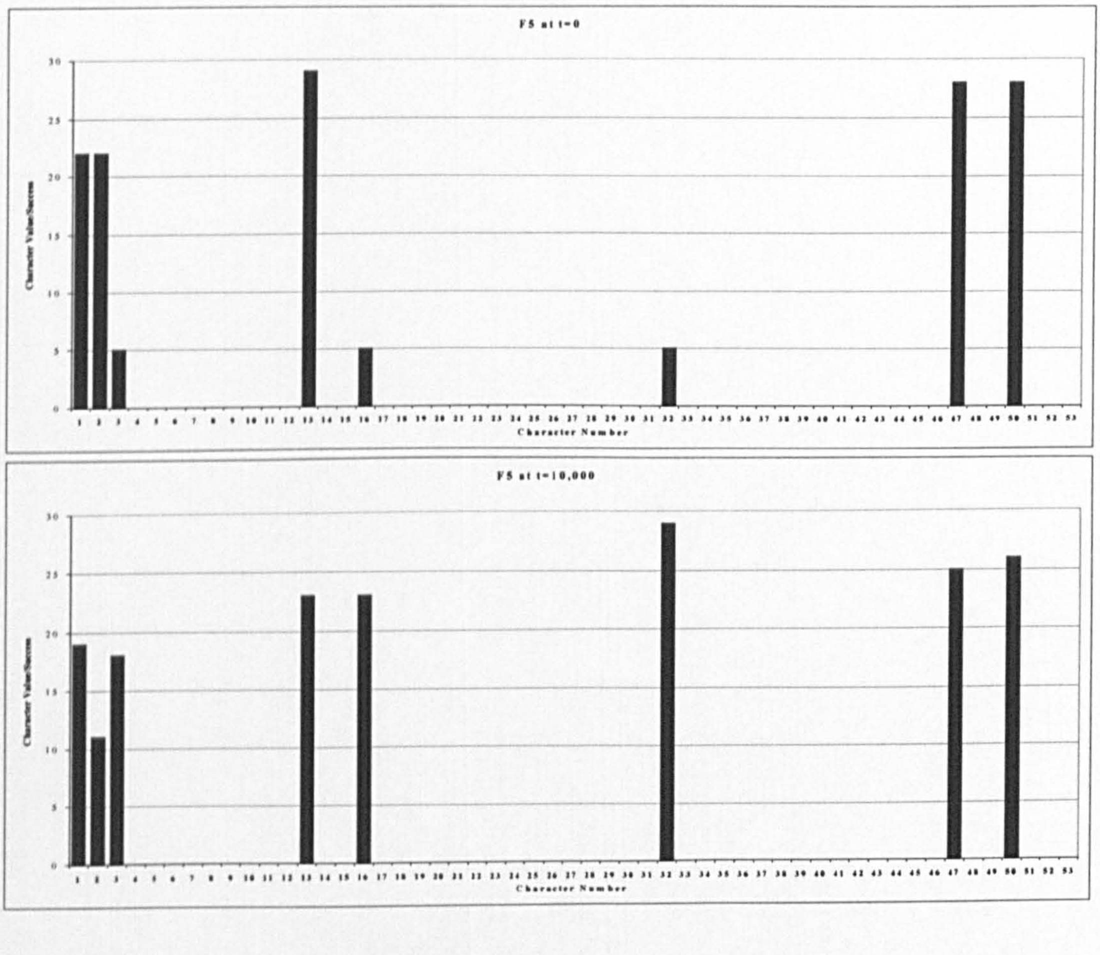
simply operate machinery, and CS 50, product focus) that define the Neocraft System. As can be seen in figure 8.3 at Time=10,000, CS 48 fails. This is a puzzling finding as this character-state is a pre-curser of all organisational forms that follow. Several reasons for this are given in chapter 9. It can be seen that CS 13 is very successful and has a final value of 29 at T=10,000. Character-state 50 also proves to be very valuable to the new organisation with a final value of 28. The original character-states from the Modern Craft Producer are also successful but their values suffer slightly with both CS 1 and CS 2 dropping 2 units and CS 50 dropping 1 unit.

Figure 8.3. Simulation of the Neocraft System from launch (Time=0) to stable solution (Time=10,000)



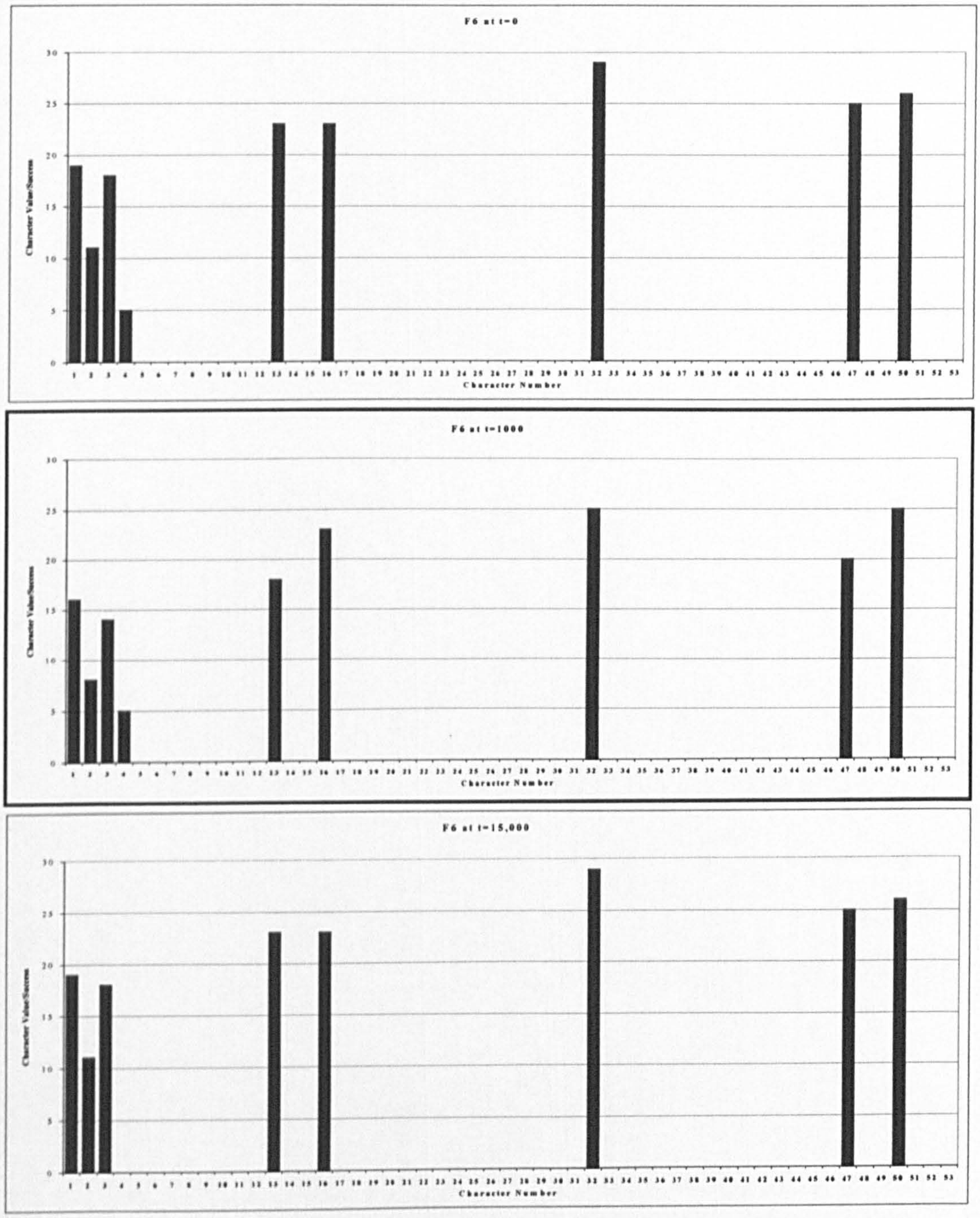
By introducing character-states 3, assembly line layout, 16, socialisation training, and 32, sequential dependency of workers, to the Neocraft System, the Skilled, Large Scale Producer is produced (see figure 8.4 at Time=0; labelled F5 in the figure). The new character-states are again introduced with a value of 5 (the Neocraft System's character-states are launched with their final value). It can be seen at the stable solution (figure 8.4 at Time=10,000) that all three new character-states survive and in fact prosper. CS 32 performs particularly well with a final value of 29. CS 16 reaches a value of 23 whilst CS 3 finishes with a value of 18. What is interesting is that although all the original character-states (from the Neocraft System) drop units of value (CS 1 by 3 units or 13.6%; CS 13 by 6 units or 20.7%; CS 47 by 3 units or 9.3%; and CS 50 by 2 units of 7%), CS 2 loses 11 units of value equating to a 50% reduction. This finding suggests that although the organisation still functions and benefits from assembly time standards, the new practices together with the original character-states reduce the significance.

Figure 8.4. Simulation of the Skilled, Large Scale Producer from launch (Time=0) to stable solution (Time=10,000)



The next simulation is quite interesting as only one characteristic separates the Skilled, Large Scale Producer and the Large Scale Producer, which is CS 4, reduction of craft skills. This is also an important characteristic in terms of all the following organisational forms. However, in this simulation the characteristic fails right from the launch (reasons for this and other character-state failures are given in chapter 9). The values for all characteristics of the Large Scale Producer at both launch and stable solution can be seen in figure 8.5.

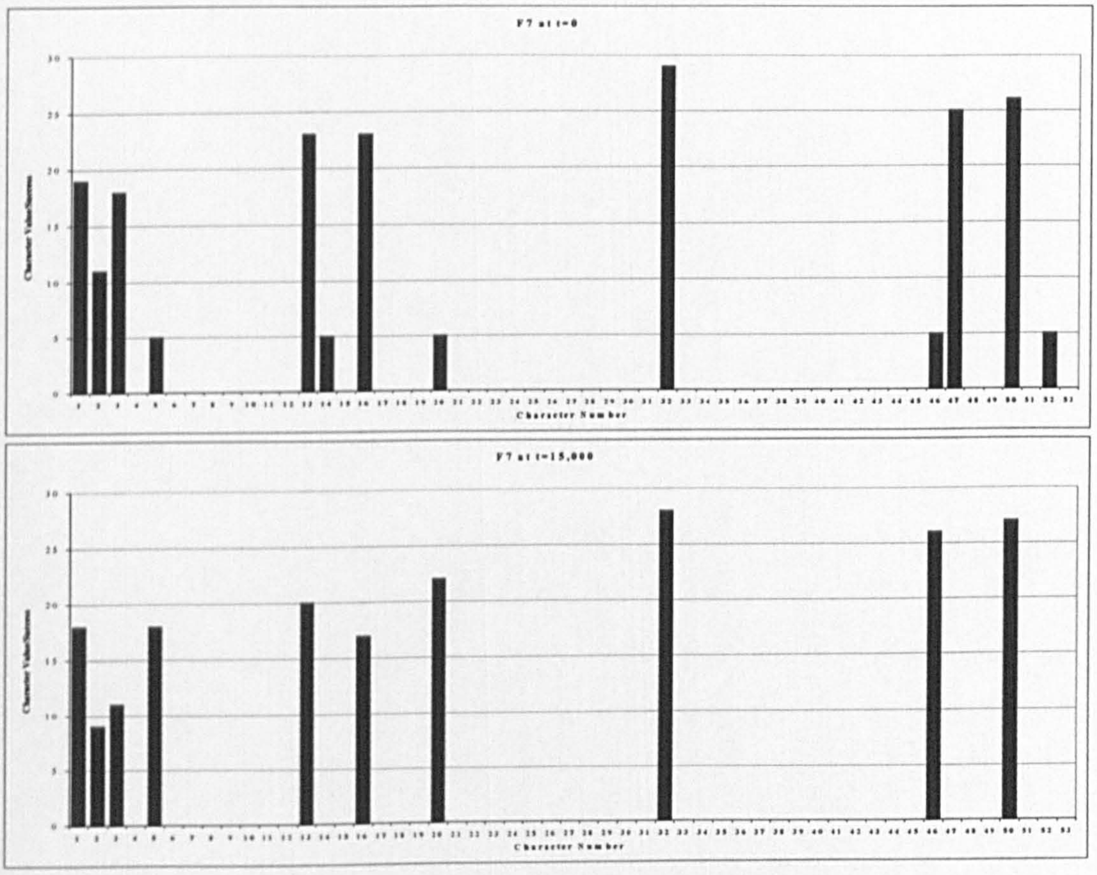
Figure 8.5. Simulation of the Large Scale Producer from launch (Time=0), at Time=1000 and at stable solution (Time=15,000)



The character-states demise, however, is a very slow process with evolutionary run taking 15,000 time units. What also can be seen in figure 8.5 at Time=1000, a relatively short period of elapsed time, is that the introduction shocks the rest of the organisation with most other character-states losing 3 to 5 units of value (e.g. character-states 1, 2, 3, 13, 32 and 47). Only CS 16, which remained the same value, and CS 50, losing only 1 unit of value, were relatively unaffected. At the end of the simulation (see figure 8.5 at Time=15,000), however, all the original character-states regained their starting values. This simulation points to the effects and consequences of introducing new technologies, practices and policies, whilst also demonstrating the potential of the model to explore such consequences and to look forward to the longer-term.

The next organisational form to evolve in the cladistic scheme is the Mass Producer (Fordism), which involves introducing character-states 5, automation (machine paced shops), 14, suppliers selected primarily on price, 20, multiple subcontracting, 46, dedicated automation, and 52, dependence on written rules. Figure 8.6 shows the organisation both at launch and at the stable solution.

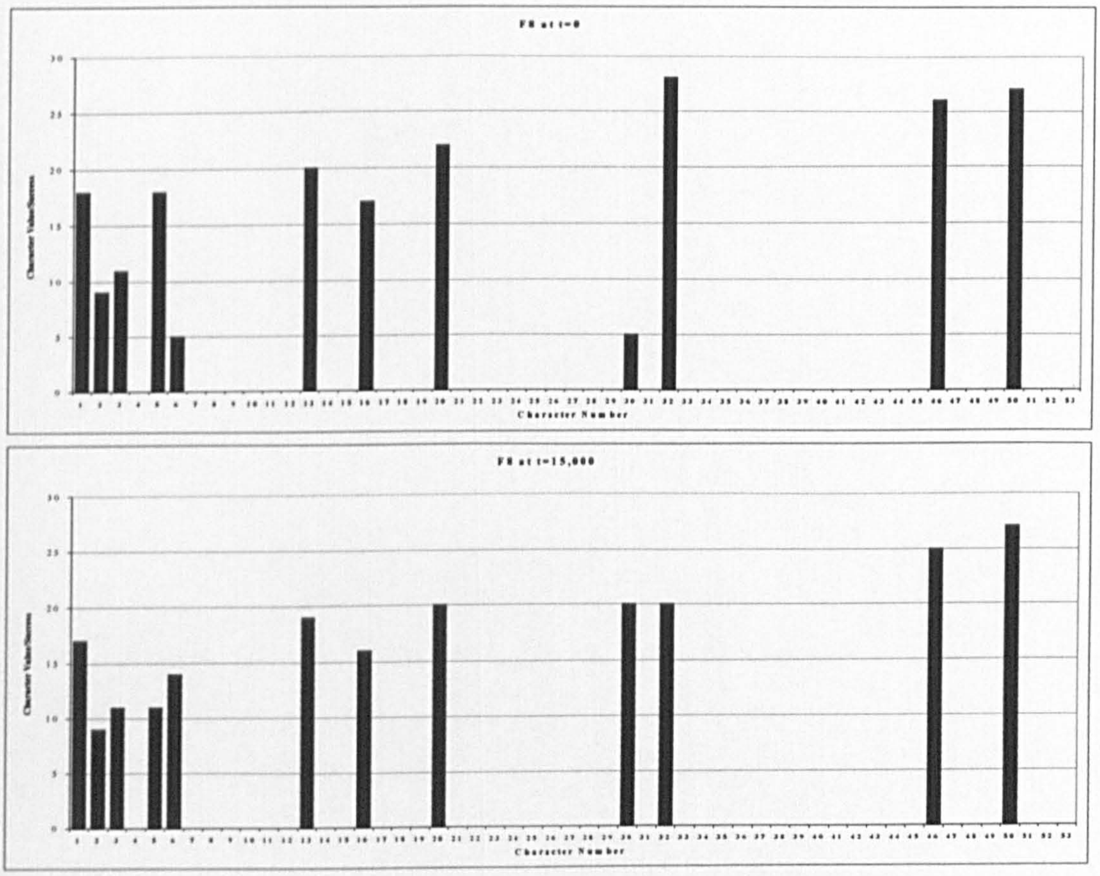
Figure 8.6. Simulation of the Mass Producer (Fordism) from launch (Time=0) to stable solution (Time=15,000)



Of the introductory character-states both character-states 14 and 52 fail from the outset. Character-state 47, which starts with a value of 25, also fails. These failings are very surprising as they are probably the most important defining attributes of the original Fordist philosophy. The largest movers, in terms of value, are the new introductions and include CS 5 which increases by 13 units, CS 20 which increases by 17 units, and CS 46 which increases by 21 units (see figure 8.6 at Time=15,000). Character-state 3 loses 7 value units, whilst CS 16 loses 6 units. The remaining characteristics either only lose 1 to 3 units (i.e. character-states 1, 2, 13 and 32) or gains 1 unit (i.e. CS 50).

By introducing character-states 6, pull production systems, and 30, preventive maintenance, the Mass Producer (Fordism) evolves into the Modern Mass Producer. As can be seen in figure 8.7 all original and introductory characteristics survived this simulation.

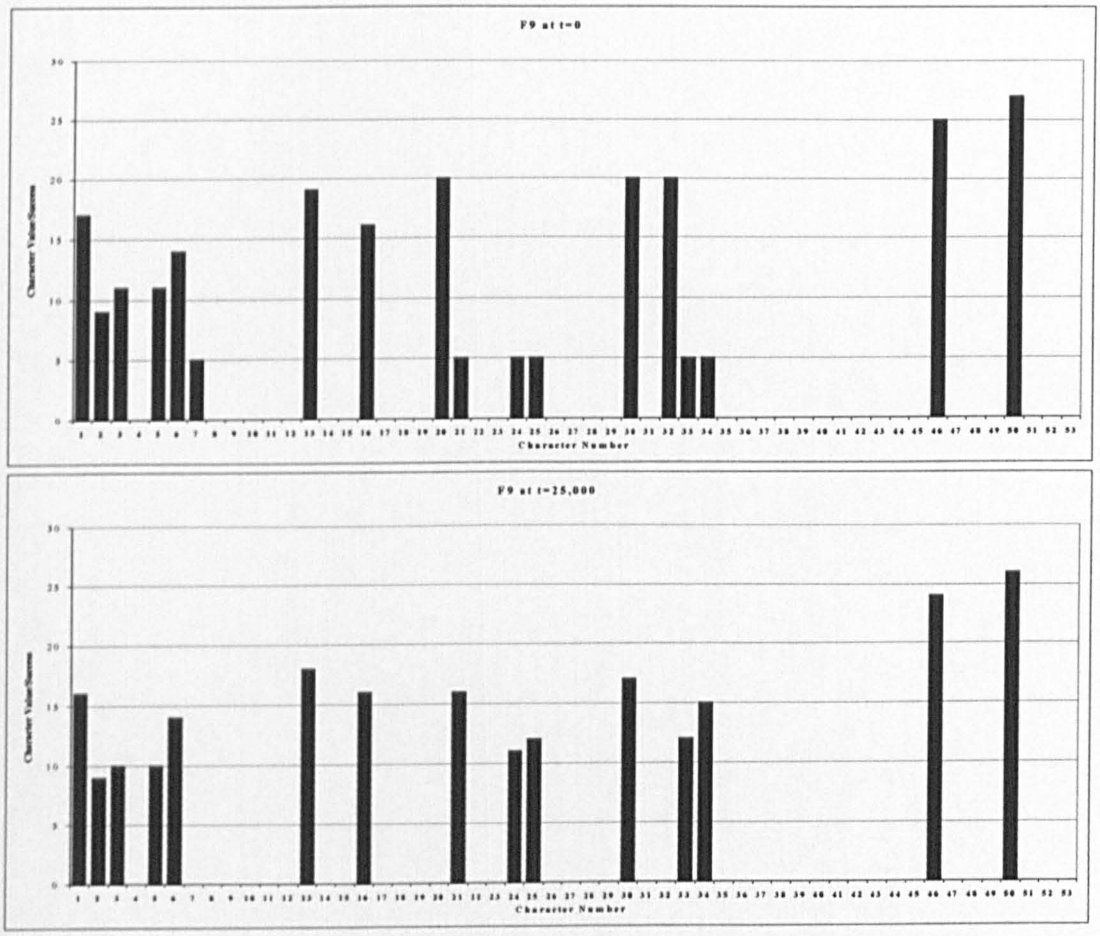
Figure 8.7. Simulation of the Modern Mass Producer from launch (Time=0) to stable solution (Time=15,000)



As the evolutionary run reached a stable solution (see figure 8.7 at T=15,000) character-states 1, 13, 16 and 46 all lost 1 unit of value, whilst CS 20 lost 2 units. Both the new introductions significantly increased in value with CS 6 increasing by 9, and CS 30 gaining 15 units of value. The biggest losers, in terms of value, were character-states 5, which dropped 7 units, and 32, which lost 8 units.

According to the cladogram the Pseudo Lean Producer evolves from the Modern Mass Producer with the addition of character-states, 7, reduction of lot size, 21, quality systems (procedures, tools, ISO 9000), 24, flexible, multifunctional workforce, 25, set-up time reduction, 33, line balancing, and 34, team policy (team motivation, pay and autonomy). All characteristics associated with the Pseudo Mass Producer, at both the simulation launch and stable solution can be seen in figure 8.8.

Figure 8.8. Simulation of the Pseudo Lean Producer from launch (Time=0) to stable solution (Time=25,000)



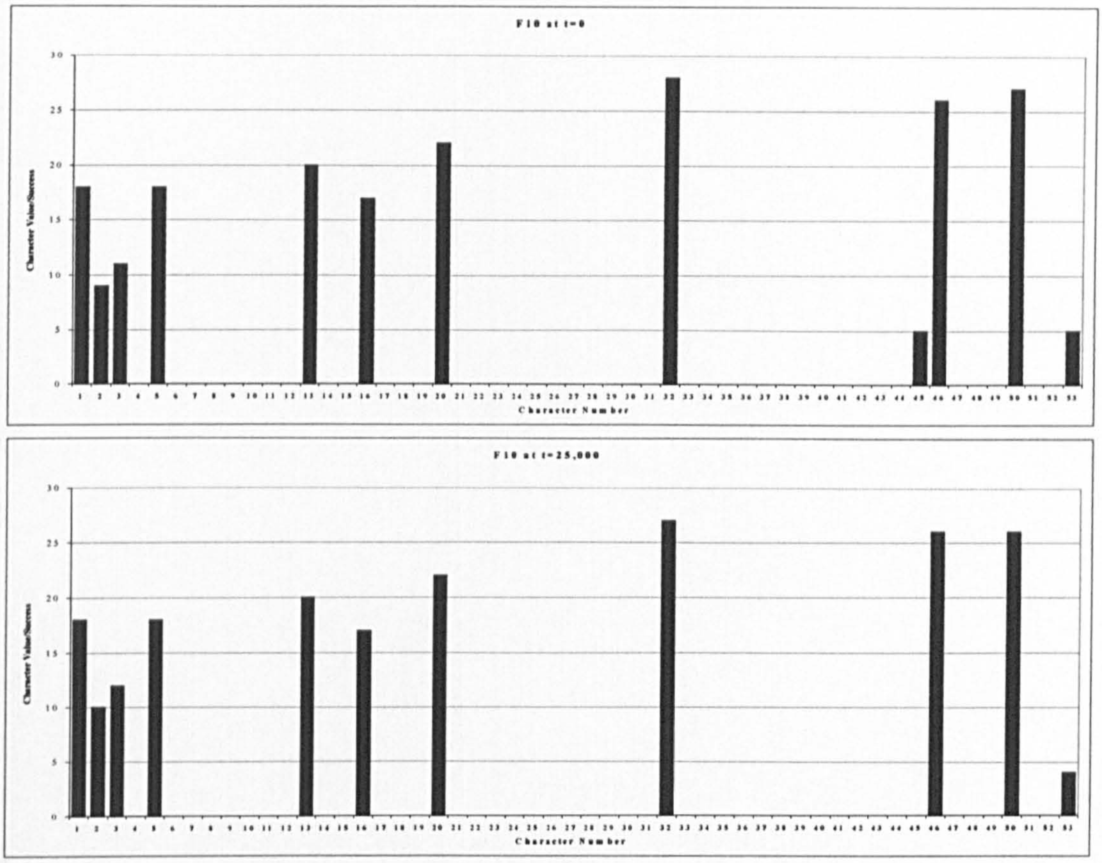
The first point to note is that the stable solution was reached after 25,000 time units a significant increase on all previous simulations (see figure 8.8). Three characteristics failed, one introductory and two of the original character-states. The introductory characteristic that failed was CS 7. The two original characteristics that failed were character-states 20 and 32, both of which had a starting value of 20 units.

Six characteristics (i.e. character-states 1, 3, 5, 13, 46 and 50) all dropped 1 value unit whereas CS 30 lost 3 units. The introductory characteristics that survived were all the biggest movers with CS 24 gaining 6 units, character-states 25 and 33 increasing by 7 units, CS 34 gaining 10 units, and CS 21 increasing by 11 units of value. Character-states 2, 6 and 16, although negatively affected during the evolutionary run, regained their starting values at the stable solution.

According to the original cladogram, the European Mass Producer is situated on a different 'branch' on the evolutionary tree and exhibits none of the introductory characteristics of the previous two organisational forms (above). Therefore the values of the characteristics of the Mass Producer (Fordism) at the stable solution are taken as the starting values for the simulation to which the introductory characteristics, that define the European Mass Producer, are added.

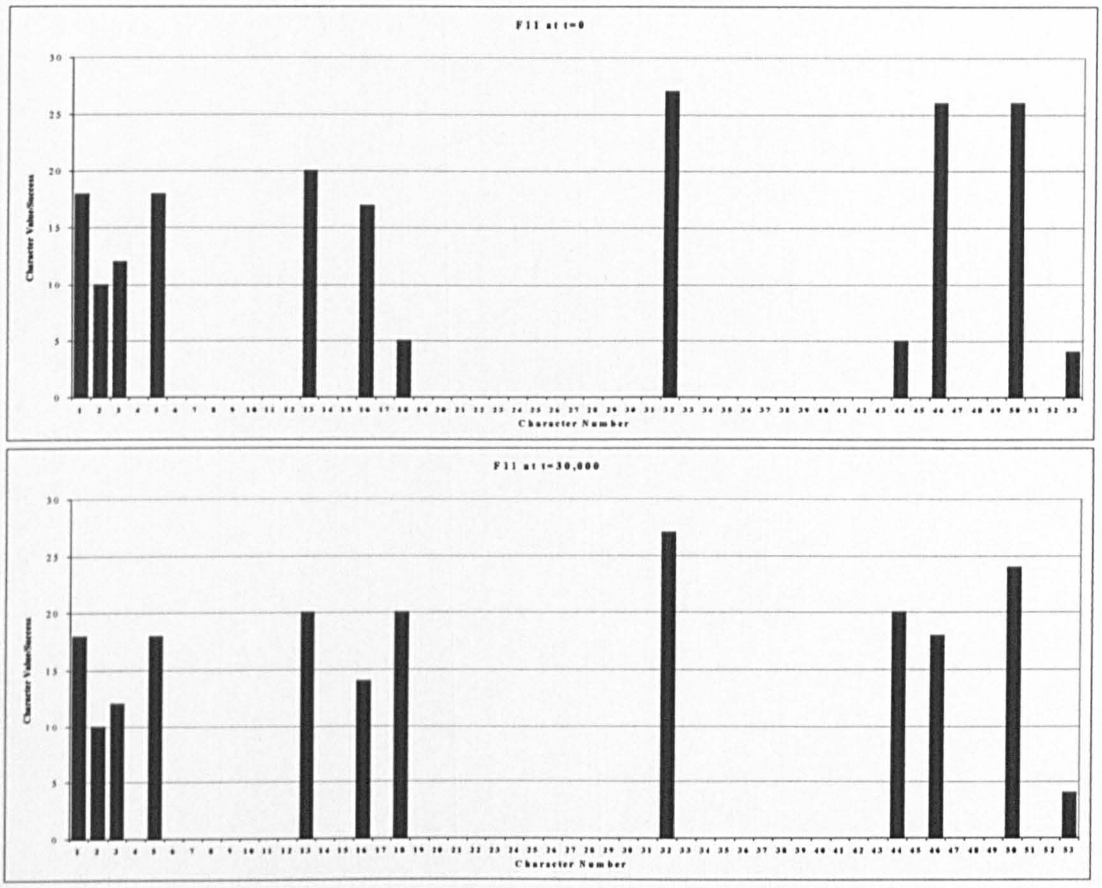
As can be seen from figure 8.9 at Time=0, there are two introductory character-states and are CS 45, immigrant workforce, and CS 53, further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible. Character-state 45 fails from the outset whereas CS 53 makes little impact finishing with 4 units of value, one unit less than the introductory value. The rest of the organisation is minimally affected (see figure 8.9 at Time=25,000) with character-states 1, 5, 13, 16, 20 and 46, after some initial slight movement, all regaining their starting values. Character-states 2 and 3 both increased by 1 unit, whilst CS 32 and CS 50 both dropped 1 unit of value.

Figure 8.9. Simulation of the European Mass Producer from launch (Time=0) to stable solution (Time=25,000)



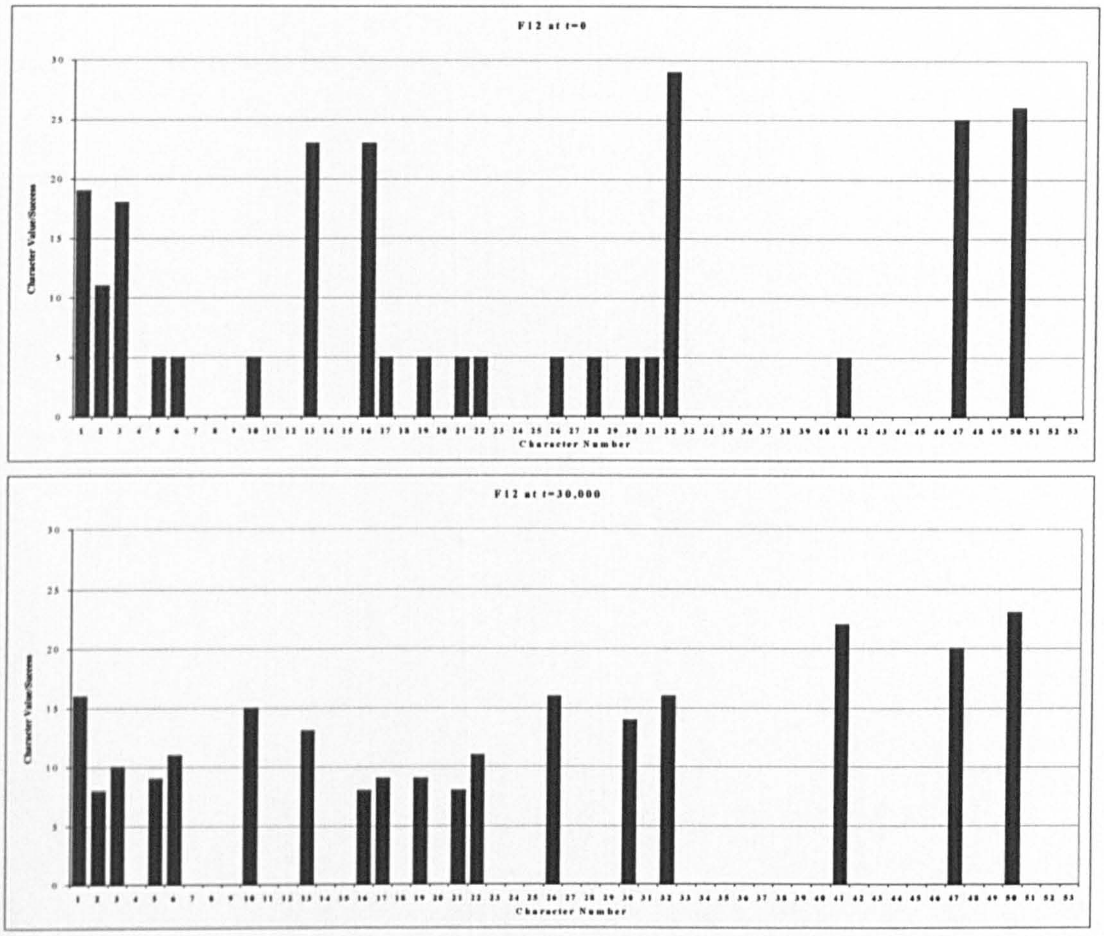
The Intensive Mass Producer exhibits two more characteristics than the European Mass Producer – CS 18, product range reduction, and CS 44 insourcing. Character-state 20, multiple subcontracting, however, is not present. The first point is that the stable solution was found approximately 30,000 time units into the evolutionary run. All starting characteristics survive the simulation (see figure 8.10). In fact many character states returned to their starting values. These include character-states 1, 2, 3, 5, 13, 32 and 53. Character-state 46 lost the most value by dropping 8 units. Character-states 13 and 50 also lost value, by 3 and 2 units, respectively. Both the introductory characteristics performed well both increasing their value by 15 units.

Figure 8.10. Simulation of the Intensive Mass Producer from launch (Time=0) to stable solution (Time=30,000)



As can be seen from the original automotive assembly plant cladogram (figure 8.1), the Just in Time System branches off from the Large Scale Producer. Figure 8.11 at Time=0 shows the original character states (from the Large Scale Producer) as well as the twelve extra introductory characteristics which include CS 5, automation (machine paced shop), CS 6, pull production system, CS 10, quality circles, CS 17, proactive training programmes, CS 19, autonomation, CS 21, quality systems, CS 22, quality philosophy, CS 26, Kaizen change management, CS 28, 100% inspection/sampling, CS 30, preventive maintenance, CS31, individual error correction, and CS 41, excess capacity. After the simulation had reached a stable solution (see figure 8.11 at Time=30,000) it can be seen that all the original character states survived although all lost at least 3 units of value. For example, character-states 1, 2 and 50 lost 3 units; CS 47 dropped 5 units; CS 3 went down 8 units; CS 13 lost 10 units; CS 32 dropped 13 units; and CS 16 went down 15 units of value.

Figure 8.11. Simulation of the Just in Time System from launch (Time=0) to stable solution (Time=30,000)

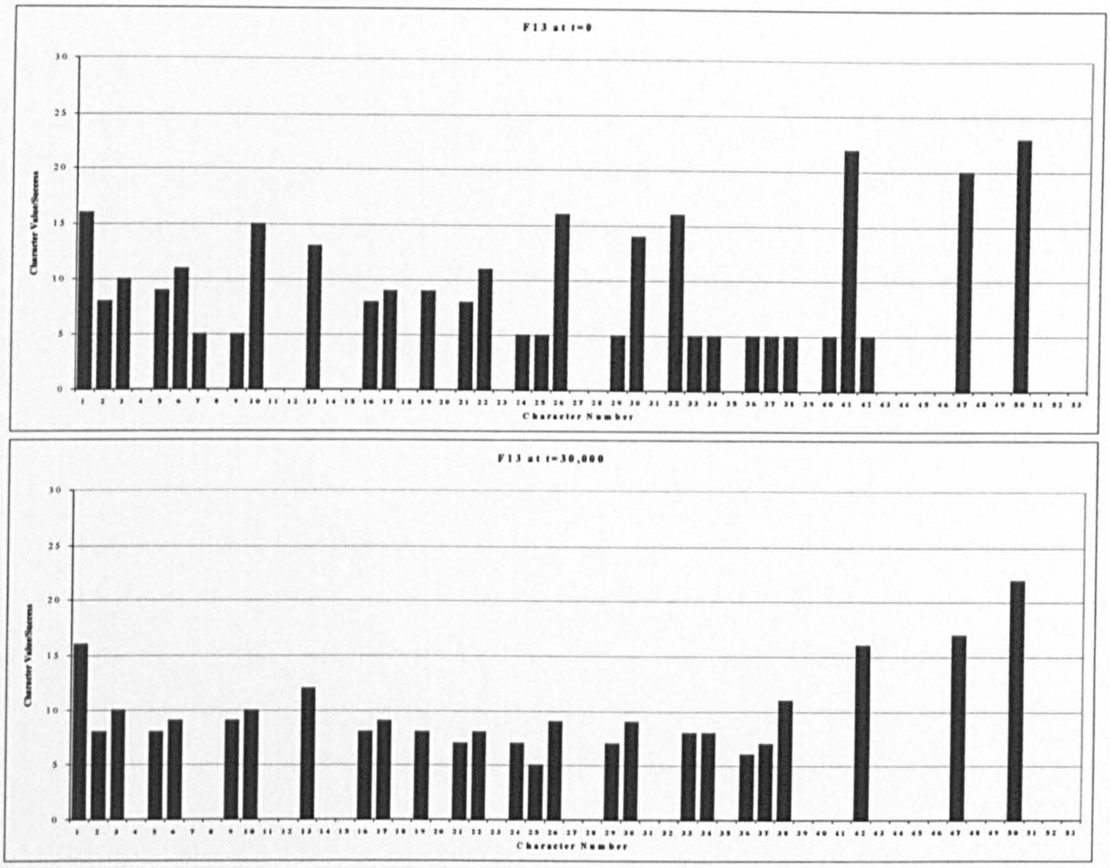


Of the introductory characteristics, CS 28 and CS 31 failed to make an impact and disappeared from the organisation (see figure 8.11). The evolutionary run, however, took quite some time to settle down and for the two character states to disappear. The remaining introductory characteristics all gained value with CS 21 gaining 3 units, character states 5, 17 and 19 increasing by 4 units, and character states 6 and 22 achieving an extra 6 units. The biggest positive movers were character-states 30, 10, 26 and 41, increasing by 9, 10, 11 and 17 units of value, respectively.

The introduction of another twelve characteristics represents the evolution of the Flexible Manufacturing System from the Just in Time System (see figure 8.12 at Time=0). The new characteristics include CS 7, reduction of lot size, CS 9, operator based machine maintenance, CS 24, flexible multifunctional workforce, CS 25, set-up time reduction, CS 29, U-shape layout, CS 33, line balancing, CS 34, team policy, CS

36, groups Vs teams, CS 37, job enrichment, CS 38, manufacturing cells, CS 40, ABC costing, and CS 42, flexible automation for product versions.

Figure 8.12. Simulation of the Flexible Manufacturing System from launch (Time=0) to stable solution (Time=30,000)

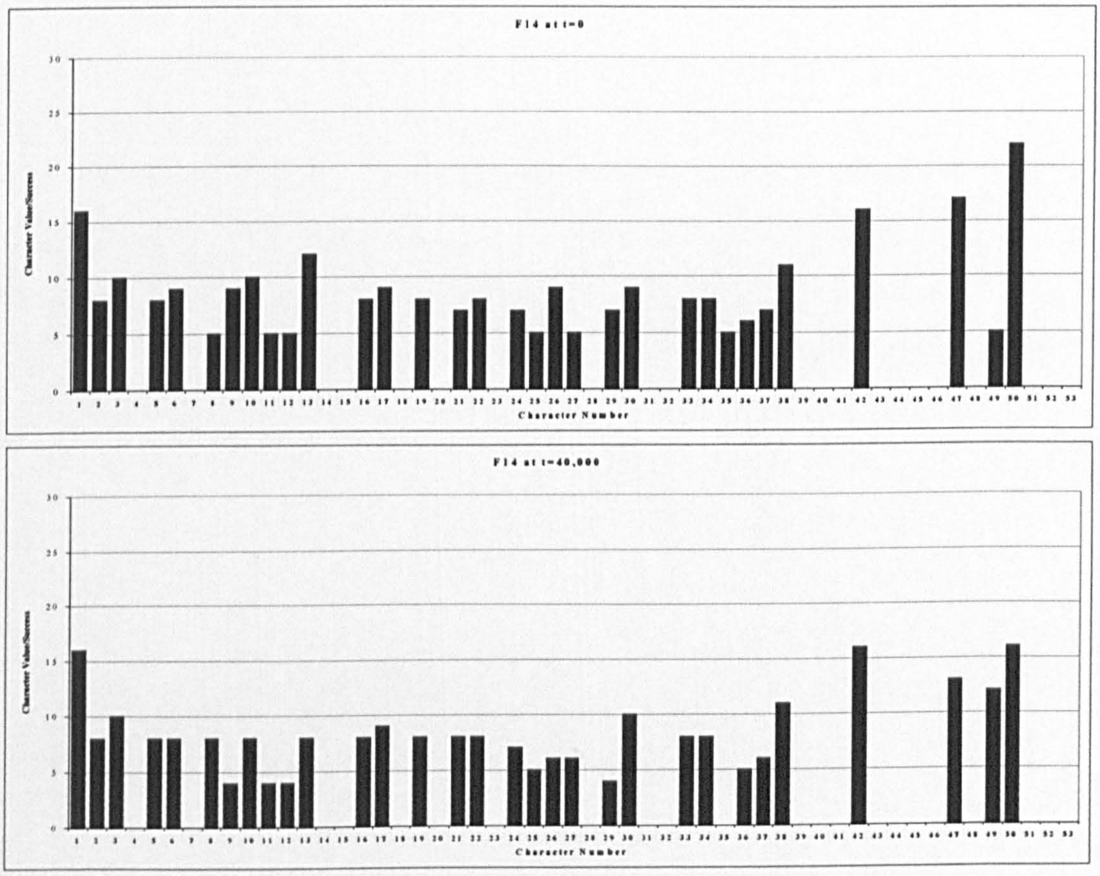


During the simulation four characteristics, two original and two introductory, performed, with respect to the rest of the organisation, badly and disappeared from the organisation (see figure 8.12 at Time=30,000). The two original characteristics were character-states 32 and 41, losing 16 and 22 units of value, respectively. The two introductory characteristics that failed were CS 7 and CS 40. In contrast to the last simulation where all characteristics lost or gained some value, six character states (i.e. 1, 2, 3, 16, 17, and 25) regained their original values after some initial movement. Of all the other characteristics there was only slight gains and losses in value with character states, in terms of negative loss, 5, 13, 19, 21, and 50 dropping 1 unit; CS 6 going down 2 units; character-states 22 and 47 losing 3 units; character-states 10 and 30 dropping 5 units; and CS 26, the biggest negative mover, losing 7 units of value. All the characteristics that lost value were the original character states.

Excluding the characteristics that failed, the introductory characteristics either stayed individual (detailed above) or gained in value. Character-state 36 gained only 1 unit; character-states 24, 29 and 37 increased by 2 units; character-states 33 and 34 added an extra 3 units; and character-states 9, 38 and 42, grew by 4, 6 and 11 units of value, respectively.

The next organisational form to evolve, according to the cladogram (see figure 8.1), is the Toyota Production System with the addition of 6 characteristics which are CS 8, pull procurement, CS 11, employee innovation prizes, CS 12, job rotation, CS 27, TQM sourcing, CS 35, Toyota verification of assembly line (TVAL), and CS 49, employees are system developers. The first point to make is that the evolutionary run increases once again in order to reach a satisfactory stable solution (see figure 8.13 at Time=40,000).

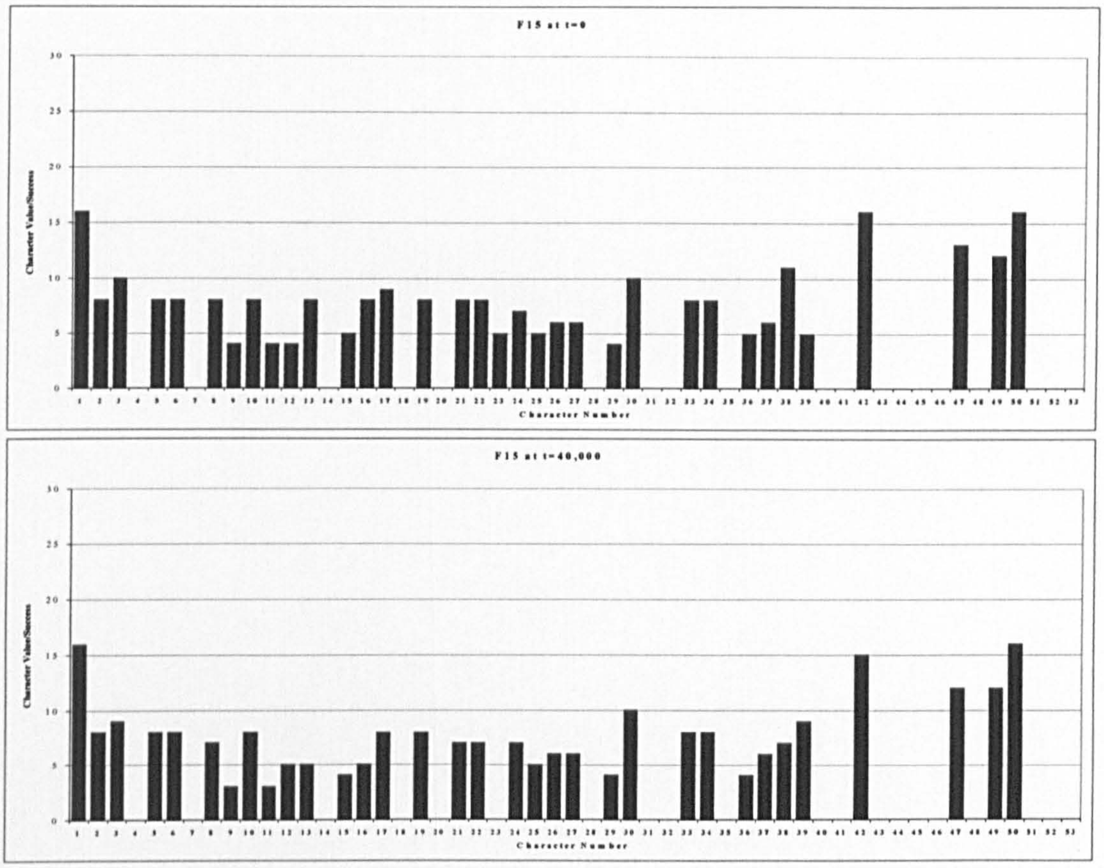
Figure 8.13. Simulation of the Toyota Production System from launch (Time=0) to stable solution (Time=40,000)



During the simulation (see figure 8.13), one characteristic, CS 35, failed. Apart from that, there was not too much activity in contrast to previous simulations. Fourteen characteristics (e.g. 1, 2, 3, 5, 16, 17, 19, 22, 24, 25, 33, 34, 38 and 42) reverted to their original values. Five character-states (i.e. 6, 11, 12, 36 and 37) lost only 1 unit of value. Character-states 10 and 29 dropped 2 and 3 units, respectively; character-states 13 and 47 lost 4 units each; and character-states 9 and 50 decreased in value by 5 and 6 units, respectively. Only five characteristics gained value with character-states 21 and 27 adding an extra 1 unit, character-states 8 and 26 increasing by 3 units, and CS 49 gaining an additional 7 units, which constituted the largest mover in either the positive or negative directions.

The addition of three characteristics to the Toyota Production Systems represents the evolution of the Lean Producer organisation (see figure 8.14 at Time=0). These are CS 15, exchange of workers with suppliers, CS 23 open book policy with suppliers and the sharing of costs, and CS 39, concurrent engineering. The simulation again took 40,000 time units to reach its most stable solution. When referring to figure 8.14 at Time=40,000, it can seen that one introductory characteristic, CS 23, failed to both make an impact and to survive. There was again very little activity in terms of value with seventeen characteristics regaining their starting values (i.e. character-states 1, 2, 5, 6, 10, 19, 24, 25, 26, 27, 29, 30, 33, 34 37, 49 and 50). Eleven characteristics lost 1 unit of value (i.e. character states 3, 8, 9, 11, 15, 17, 21, 22, 36, 42, and 47). Character states 13 and 16 dropped 3 units whereas CS 38 decreased by four units of value. Only two characteristics, one original and one introductory, gained any value with CS 12 increasing by 1 and CS 39 adding 4 units of value.

Figure 8.14. Simulation of the Lean Producer from launch (Time=0) to stable solution (Time=40,000)



The evolution of the Agile Producer from the Lean Producer, according to the automotive assembly plant cladogram seen in figure 8.1, involves the introduction of only two characteristics, CS 43, agile automation for different products, and CS 51, parallel processing (see figure 8.15 at Time=0). One characteristic belonging to the original set, CS 13, which had been in decline during the last several simulations, failed (see figure 8.15 at Time=40,000). Six characteristics lost value with three (i.e. character-states 5, 29 and 47) losing 1 unit and character-states 49, 42 and 50 dropping 2, 6 and 10 units of value, respectively. Seven characteristics gained in value including the introductory characteristics with three (i.e. character-states 8, 38 and 39) increasing by 1 unit and character-states 15, 12, 43 and 51 adding extra 2, 4, 5, and 11 units of value, respectively.

Figure 8.15. Simulation of the Agile Producer from launch (Time=0) to stable solution (Time=40,000)

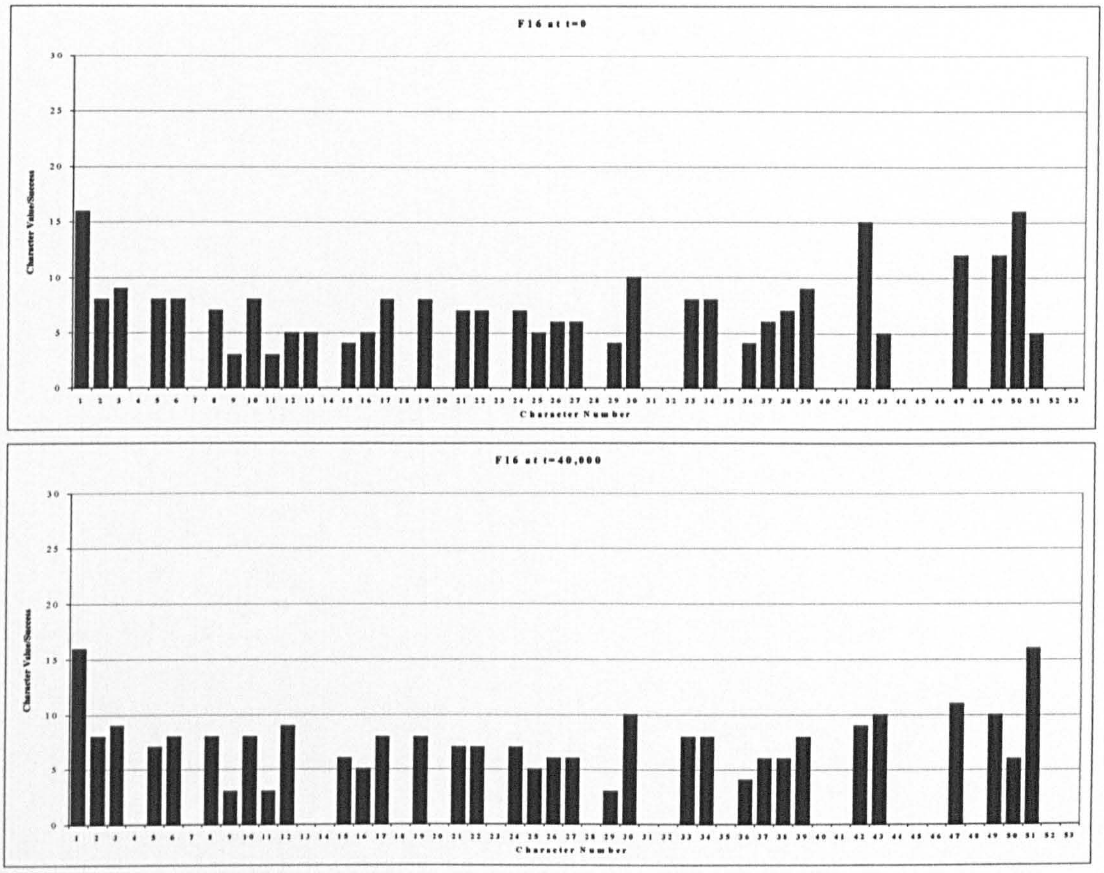


Table 8.3 summarises the full evolutionary procedure and the main details of each simulation in terms of:

- Organisational forms
- The characteristics that failed during each simulation
- The remaining characteristics of each organisational form
- The cumulative characteristics that failed
- The total time taken for the simulation to stabilise.

Table 8.3. Table of simulation results for the organisational forms and their characteristics for the full simulated evolutionary procedure

	Organisational Form	Failed Characteristics	Remaining Characteristics	Total Failed Characteristics	Total Time
1	Ancient Craft Systems	Not Simulated		N/A	
2	Standardised Craft Systems	Not Simulated	1	N/A	
3	Modern Craft Systems	None	1, 2, 47	None	10,000
4	Neocraft Systems	48	1, 2, 13, 47, 50	48	10,000
5	Skilled Large Scale Producers	None	1, 2, 3, 13, 16, 32, 47, 50	48	10,000
6	Large Scale Producers	4	1, 2, 3, 13, 16, 32, 47, 50	4, 48	15,000
7	Mass Producers (Fordism)	14, 47, 52	1, 2, 3, 5, 13, 16, 20, 32, 46, 50	4, 14, 47, 48, 52	15,000
8	Modern Mass Producers	None	1, 2, 3, 5, 6, 13, 16, 20, 30, 32, 46, 50	4, 14, 47, 48, 52	15,000
9	Pseudo Lean Producers	7, 20, 32	1, 2, 3, 5, 6, 13, 16, 21, 24, 25, 30, 33, 34, 46, 50	4, 7, 14, 20, 32, 47, 48, 52	25,000
10	European Mass Producers	45	1, 2, 3, 5, 13, 16, 20, 32, 46, 50, 53	4, 14, 45, 47, 48, 52	25,000
11	Intensive Mass Producers	None	1, 2, 3, 5, 13, 16, 18, 32, 44, 46, 50, 53	4, 14, 45, 47, 48, 52	30,000
12	Just In Time Systems	28, 31	1, 2, 3, 5, 6, 10, 13, 16, 17, 19, 21, 22, 26, 30, 32, 41, 47, 50	4, 28, 31, 48	30,000
13	Flexible Manufacturing Systems	7, 32, 40, 41	1, 2, 3, 5, 6, 9, 10, 13, 16, 17, 19, 21, 22, 24, 25, 26, 29, 30, 33, 34, 36, 37, 38, 42, 47, 50	4, 7, 28, 31, 32, 40, 41, 48	30,000
14	Toyota Production Systems	35	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 13, 16, 17, 19, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 42, 47, 49, 50	4, 7, 28, 31, 32, 35, 40, 41, 48	40,000
15	Lean Producers	23	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 13, 15, 16, 17, 19, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 39, 42, 47, 49, 50	4, 7, 23, 28, 31, 32, 35, 40, 41, 48	40,000
16	Agile Producers	13	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 15, 16, 17, 19, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 39, 42, 43, 47, 49, 50, 51	4, 7, 13, 15, 23, 28, 31, 32, 35, 40, 41, 48	40,000

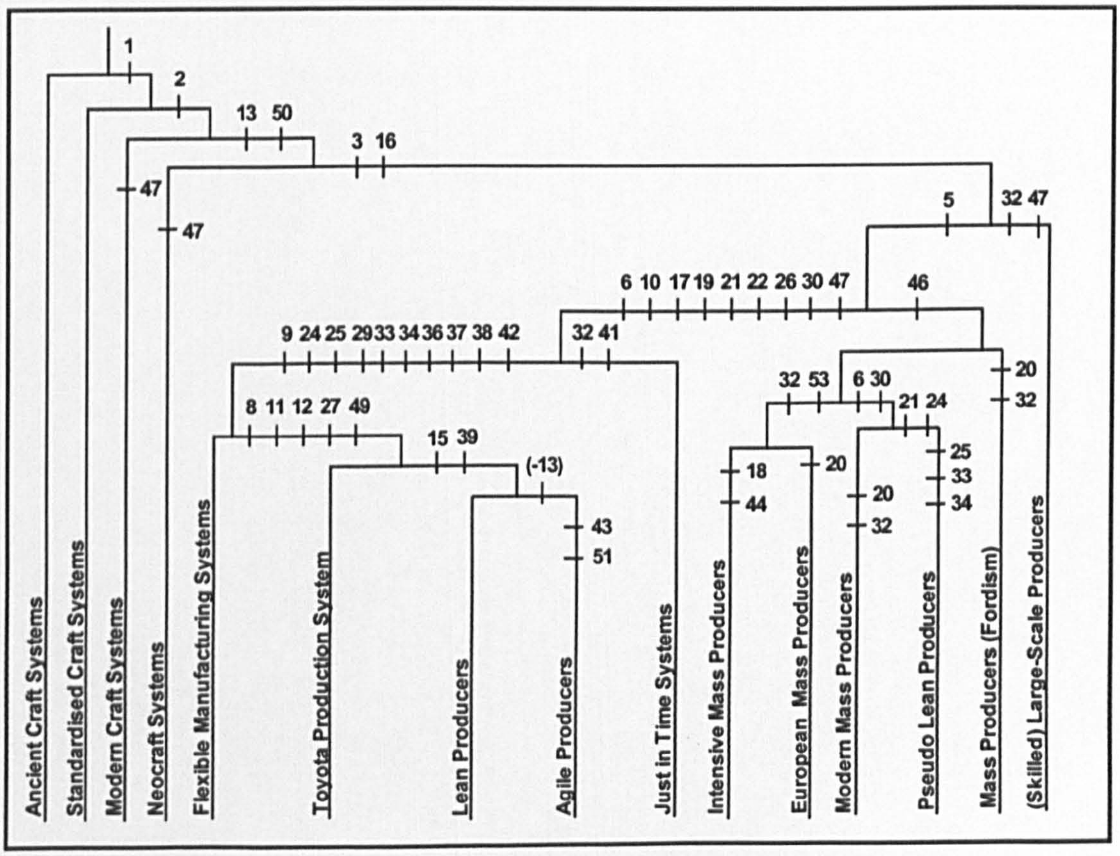
From these results, an amended cladogram of the automotive assembly plant organisations may now be constructed. Before discussing the amended cladogram, however, it is interesting to firstly note that eleven characteristics (character-states 4, 7, 14, 23, 28, 31, 35, 40, 45, 48 and 52) of the original cladogram failed altogether and as such have been deleted from the amended cladogram (see table 8.4 for all the characteristics with the failed characteristics highlighted). Although many more characteristics failed during individual simulations, the eleven identified above failed in their introductory simulation (with CS 7 being introduced on two occasions) and as such cannot be recorded on the cladogram as stable characteristics.

Table 8.4. Amended characteristics of automotive assembly plants according to the full evolutionary simulations

1. Standardisation of parts
2. Assembly time standards
3. Assembly line layout
4. Reduction of craft skills
5. Automation (machine paced shop)
6. Pull production system
7. Reduction of lot size
8. Pull procurement
9. Operator based machine maintenance
10. Quality circles
11. Employee innovation prizes
12. Job rotation
13. Large volume production
14. Suppliers selected primarily on price
15. Exchange of workers with suppliers
16. Socialisation training (master/apprentice learning)
17. Proactive training programs
18. Product range reduction
19. Autonomation
20. Multiple sub-contracting
21. Quality systems (tools, procedures, ISO9000)
22. Quality philosophy (TQM, way of working, culture)
23. Open book policy with suppliers; sharing of cost
24. Flexible multi-functional workforce
25. Set-up time reduction
26. Kaizen change management
27. TQM sourcing; suppliers selected on basis of quality
28. 100% inspection/sampling
29. U-shape layout
30. Preventive maintenance
31. Individual error correction; products are not re-routed to a special fixing station
32. Sequential dependency of workers
33. Line balancing
34. Team policy (motivation, pay and autonomy for team)
35. Toyota verification of assembly line (TVAL)
36. Groups vs teams
37. Job enrichment
38. Manufacturing cells'
39. Concurrent engineering
40. ABC costing
41. Excess capacity
42. Flexible automation for product versions
43. Agile automation for different products
44. Insourcing
45. Immigrant workforce
46. Dedicated automation
47. Division of labour
48. Employees are system tools and simply operate machines
49. Employees are system developers; if motivated and managed they can solve problems and create value
50. Product focus
51. Parallel processing
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity
53. Further intensification of labour; employees are considered part of the machine and will be replaced by a machine if possible

Figure 8.16 shows the amended automotive assembly plant cladogram taken from the results of the full evolutionary run. It can be seen that there are several changes which completely change the nature of the cladogram and the evolutionary history.

Figure 8.16. Amended automotive assembly plant cladogram according to full evolutionary simulation



The most fundamental change to the cladogram is that the Large-Scale Producer, with the failure of CS 4, now cannot be distinguished from the Skilled, Large-Scale Producer (e.g. compare figure 8.1 with figure 8.16). This means that instead of 16 organisational forms (defined by 53 characteristics) in the original manufacturing cladistics work, there are only 15 organisational forms (defined by 42 characteristics). It is clear when looking at the history of the automotive industry (e.g. Womack et al, 1990) that the distinguishing feature between Skilled, Large-Scale Production and Large-Scale production is the actual reduction of craft skills (i.e. character-state 4).

The evolutionary simulations suggest (if the data are taken to be reliable) that for reduction of craft skills to persist it needs other certain defining characteristics that would act as a synergetic bundle. This therefore suggests that further research needs to be conducted to refine the hypotheses contained within the cladogram. However, as mentioned in chapter 7 concerning methodology, the data that was collected was from a general manufacturing population and therefore has a bearing on this conclusion (a more in-depth discussion of this can be found in chapter 9).

There are several points also to be made concerning the distribution of the failed characteristics (as well as the distribution of the original characteristics). According to the original manufacturing cladistics work, the first six organisational forms are defined by 10 characteristics. Of these, three characteristics failed equating to 30% reduction of characteristics (as well as one less organisational form).

The five organisational forms belonging to the branch of the mass producers are defined by a further 16 characteristics, three of which failed during the simulations. However, eight of these sixteen characteristics also appear on the lean side of the cladogram. Therefore, only eight characteristics exclusively define the mass producers, 3 of which failed (equating to a 37.5% reduction of characteristics), leaving only 5 characteristics exclusive to the five mass producers in the amended cladogram.

When analysing the leaner production side of the evolutionary scheme in this way, it can be seen that, firstly, there are in total 34 characteristics in the original manufacturing cladistics work, eight of which are also common to the mass production side. Six characteristics failed, five of which were exclusive to the leaner production side of the scheme, leaving 21 characteristics exclusive to the 5 leaner producers (a 23% reduction of characteristics).

There are several other consequences of the failures of the individual characteristics in terms of the cladogram. The first point to make is that of the first several characteristics to emerge, CS 48 no longer plays a part. In addition, CS 32 moves position. In the original cladogram CS 32 was a feature of all organisations that evolved after the Skilled, Large-Scale Producer (present in 12 organisational forms). Through the simulations, however, the characteristic became unstable and failed in all but one organisation on the leaner production side (the Just in Time System) as well as the Pseudo Lean Producer on the mass production side of the scheme.

A similar situation arises for CS 47, which in the original work featured in all organisations that evolved after the Standardised Craft System (14 of the 16 organisational forms). However, the simulations found the characteristic to be unstable in all the organisations on the mass production side of the scheme. As can be seen in figure 8.16, this changes the labelling of characteristics on the cladogram.

Character-state 41 also shifts position. In the original work, the characteristic was present in all organisations on the leaner production side. The simulation work found it to be stable only in the Just in Time System. In the original cladogram, CS 20 was present in all but the Intensive Mass Producer on the mass production side of the scheme. Through the simulations, it was also found to be unstable in the Pseudo Lean Producer, which, in practical terms, changes the labelling of character-states on the cladogram. There are other changes in the cladogram (i.e. the deletion of character-states 7, 14, 23, 28, 31, 35, 40, 45, 52) but do not significantly change the structure of the evolutionary scheme.

8.2. Tracking the Performance of Character-States

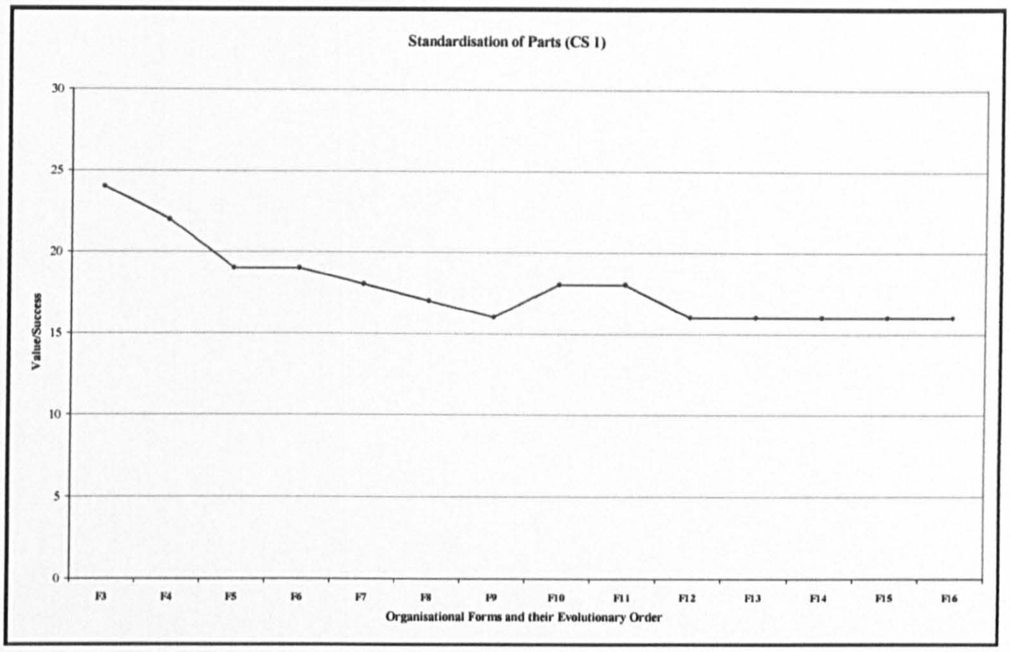
It is also interesting, in terms of both the effects of the different organisations on the character-states and to gain another perspective of the evolutionary history, to track the performance of individual characteristics throughout the evolutionary run. Table 8.5 consists of each organisational form, the individual characteristics and their performance in terms of value units at the stable solution of each simulation. Nine characteristics (i.e. character-states 1, 2, 3, 5, 13, 16, 32, 47 and 50) were selected for further analysis, highlighted grey in the table, to get a deeper insight into the 'fit', effectiveness and/or idiosyncrasies of different characteristics with respect to the overarching organisations.

Table 8.5. Values of the characteristics at the stable solution for each simulation

Character-state	Modern Craft System	Neocraft System	Skilled, Large-Scale Producer	Large-Scale Producer	Mass Producer (Fordism)	Modern Mass Producer	Pseudo Lean Producer	European Mass Producer	Intensive Mass Producer	Just in Time System	Flexible Manufacturing System	Toyota Production System	Lean Producer	Agile Producer
1	24	22	19	19	18	17	16	18	18	16	16	16	16	16
2	24	22	11	11	9	9	9	10	10	8	8	8	8	8
3	0	0	18	18	11	11	10	12	12	10	10	10	9	9
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	18	11	10	18	18	9	8	8	8	7
6	0	0	0	0	0	14	14	0	0	11	9	8	8	8
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	8	7	8
9	0	0	0	0	0	0	0	0	0	0	9	4	3	3
10	0	0	0	0	0	0	0	0	0	15	10	8	8	8
11	0	0	0	0	0	0	0	0	0	0	0	4	3	3
12	0	0	0	0	0	0	0	0	0	0	0	4	5	9
13	0	29	23	23	20	19	18	20	20	13	12	8	5	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	4	6
16	0	0	23	23	17	16	16	17	14	8	8	8	5	5
17	0	0	0	0	0	0	0	0	0	9	9	9	8	8
18	0	0	0	0	0	0	0	0	20	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	9	8	8	8	8
20	0	0	0	0	22	20	0	22	0	0	0	0	0	0
21	0	0	0	0	0	0	16	0	0	8	7	8	7	7
22	0	0	0	0	0	0	0	0	0	11	8	8	7	7
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	11	0	0	0	7	7	7	7
25	0	0	0	0	0	0	12	0	0	0	5	5	5	5
26	0	0	0	0	0	0	0	0	0	16	9	6	6	6
27	0	0	0	0	0	0	0	0	0	0	0	6	6	6
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	7	4	4	3
30	0	0	0	0	0	20	17	0	0	14	9	10	10	10
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0
32	0	0	29	29	28	20	0	27	27	16	0	0	0	0
33	0	0	0	0	0	0	12	0	0	0	8	8	8	8
34	0	0	0	0	0	0	15	0	0	0	8	8	8	8
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	6	5	4	4
37	0	0	0	0	0	0	0	0	0	0	7	6	6	6
38	0	0	0	0	0	0	0	0	0	0	11	11	7	6
39	0	0	0	0	0	0	0	0	0	0	0	0	9	8
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	0	0	0	22	0	0	0	0
42	0	0	0	0	0	0	0	0	0	0	16	16	15	9
43	0	0	0	0	0	0	0	0	0	0	0	0	0	10
44	0	0	0	0	0	0	0	0	20	0	0	0	0	0
45	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	26	25	24	26	18	0	0	0	0	0
47	29	28	25	25	0	0	0	0	0	20	17	13	12	11
48	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	12	12	10
50	0	28	26	26	27	27	26	26	24	23	22	16	16	6
51	0	0	0	0	0	0	0	0	0	0	0	0	0	16
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	4	4	0	0	0	0	0

The graph of CS 1, standardisation of parts, maps out the value at the stable solution with respect to each organisational form (see figure 8.17). This characteristic, compared to all others, was the most successful in terms of both most organisations and the full evolutionary run from Modern Craft System to Agile Producer.

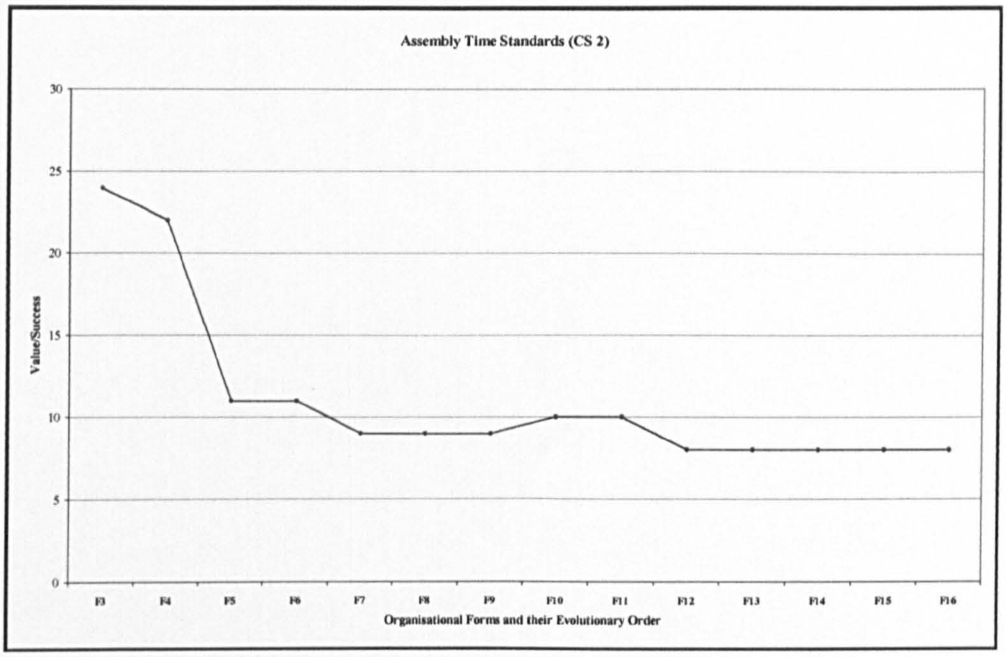
Figure 8.17. The value performance of character-state 1 throughout the simulations



It can be seen that CS 1 began very well with a value of 24 units but gradually declined throughout the evolutionary run to a value of 16. The gradual decline was interrupted as the characteristic increased by 3 units, performing a little better in both the European and Intensive Mass Producers. However, as the 'leaner' part of the cladogram was simulated the characteristic dropped those 3 value units and remained at a value of 16 until the simulations had finished – two thirds of its starting value.

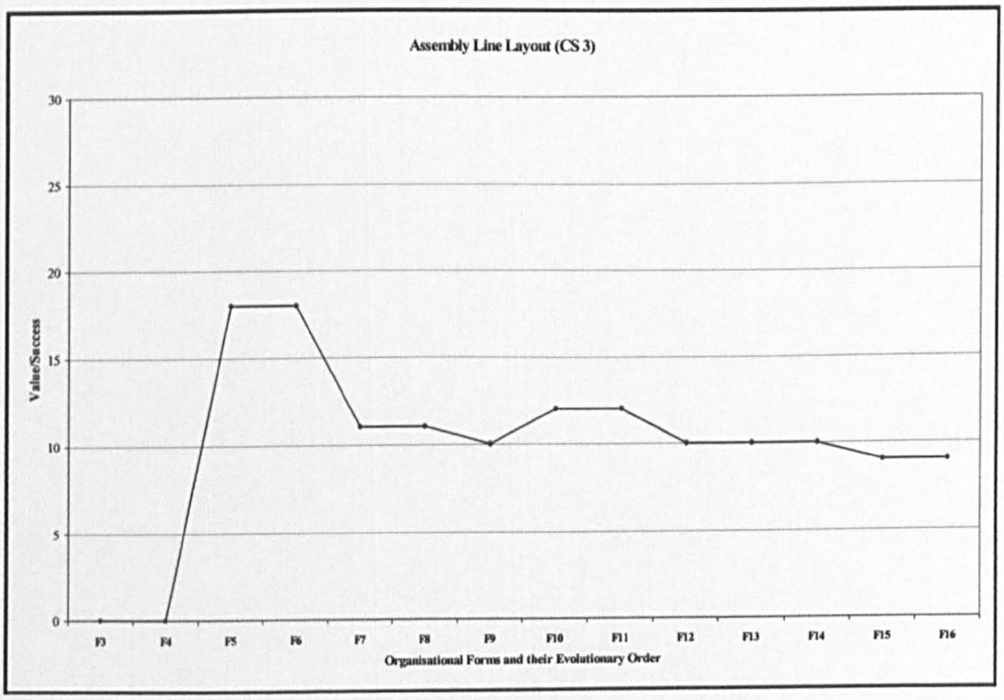
As can be seen from figure 8.18, character-state 2, assembly time standards, displayed a similar pattern. The characteristic started well with 24 units of value at the end of the first simulation. It then dropped 2 units in the second simulation. However, CS 2 lost significant value (11 units) during the simulation of the Skilled, Large-Scale Producer and stabilised at approximately 11, equating to a 50% loss. This loss may have been in part attributed to the introduction of character-states 3, 4, 16 and 32. This is in contrast to CS 1 which lost only 3 value units or just less than 14% of its value. The characteristic again increased slightly by 1 unit during the European and Intensive Mass Producers' simulations, but dropped 2 units and levelled off at 8 value units for the remaining simulations of the leaner side of the evolutionary tree, which was one third of its starting value.

Figure 8.18. The value performance of character-state 2 throughout the simulations



Character-state 3, assembly line layout, first emerges in the Skilled, Large-Scale Producer and stabilised at a healthy 18 units of value, which was maintained during the simulation of the Large-Scale Producer (see figure 8.19).

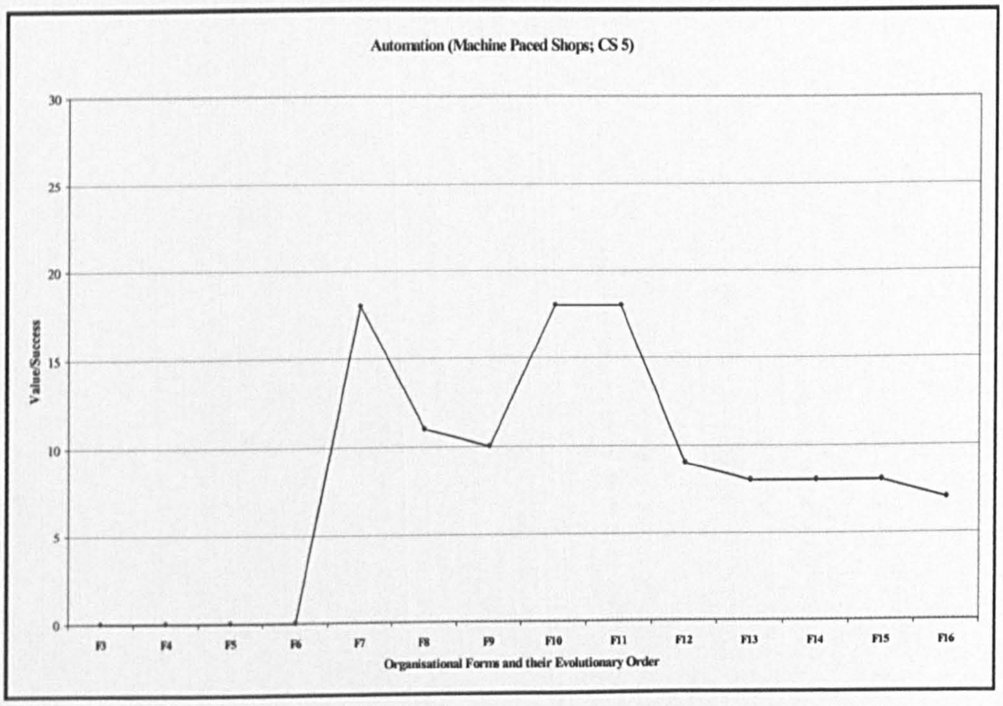
Figure 8.19. The value performance of character-state 3 throughout the simulations



The value however declined by 7 units (i.e. 39%) during the simulations of the first three organisations on the mass producer side of the evolutionary scheme. The value again increased during the simulations of the European and Intensive Mass Producers but lost this value in the first three organisations on the leaner side of the evolutionary tree. The characteristic dropped a further unit of value for the Lean and Agile Producers and ended with 9 units, equating to approximately half its starting value.

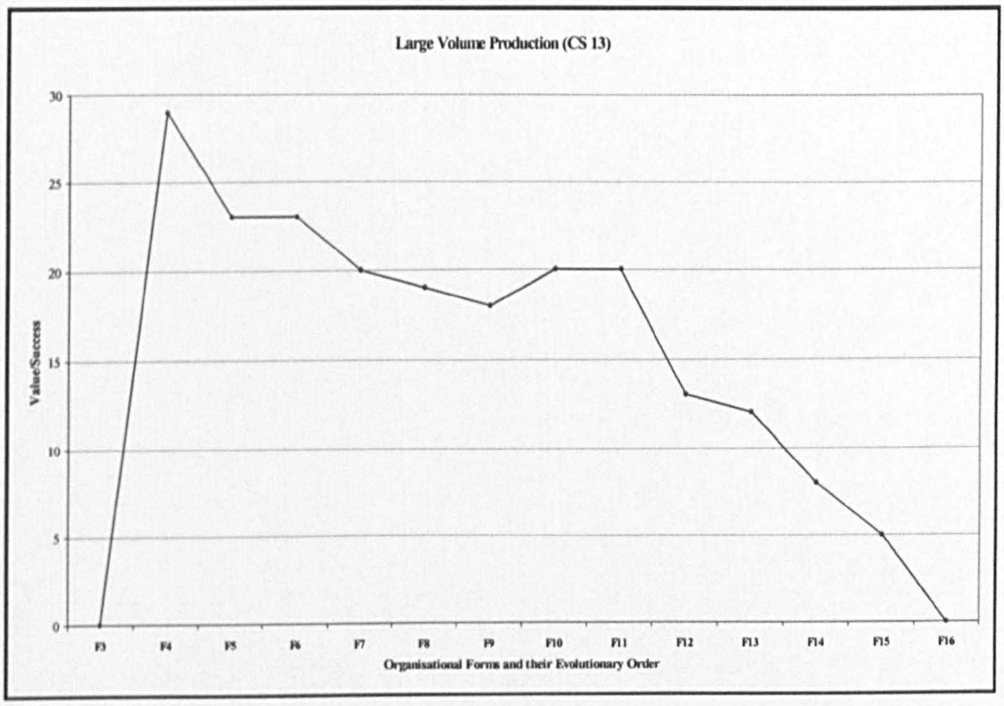
Figure 8.20 shows that CS 5, automation (machine paced shops), is introduced at the beginning of the simulation of the Mass Producer (Fordism) and ended with a healthy 18 units of value. This value declined, however, during the next two simulations dropping 7 units of value in the first simulation (the Modern Mass Producer) and a further 1 unit in the second (Pseudo Lean Producer). An increase in value occurred again (as with all the previous characteristics discussed) during the simulations of the European and Intensive Mass producers. This time however, the increase was far more pronounced as the characteristic gained 8 value units, an 80% increase, and regained the stabilisation value of its first introduction (i.e. approximately 18 units). Nonetheless the increase was only mirrored by the decrease in value during the remaining simulations dropping an average of approximately 10 units with a final value of 7 units, just short of 39% of its initial value at the end of the first simulation.

Figure 8.20. The value performance of character-state 5 throughout the simulations



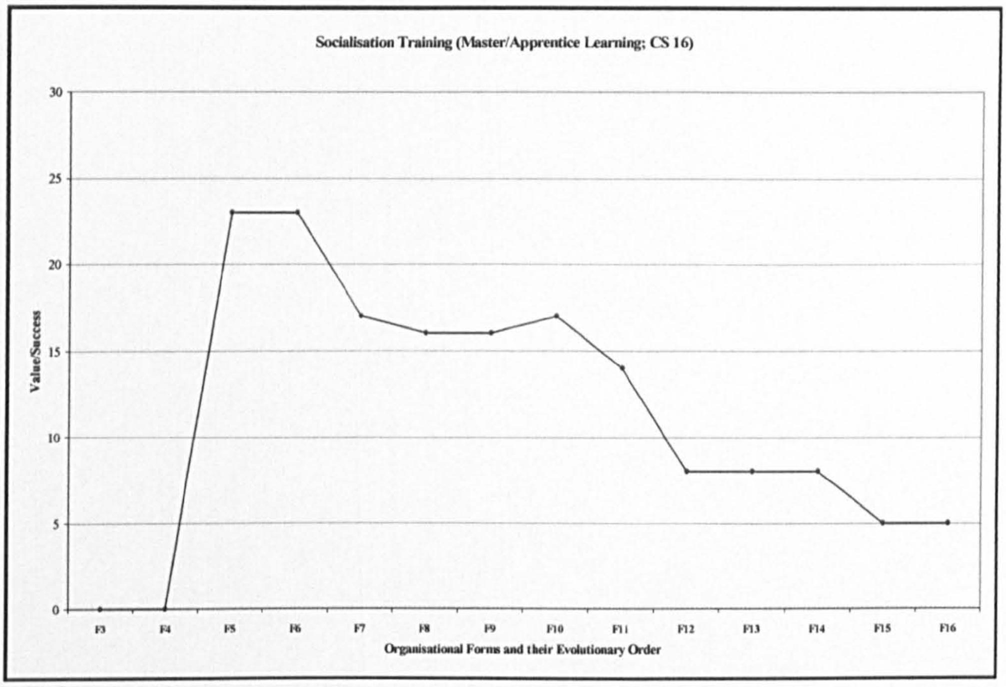
As can be seen from figure 8.21, the introduction of character-state 13, large volume production, is an instant success and stabilises with the highest value score, when compared to the other characteristics, of approximately 29 units matched only by character-states 32 and 47. This success is short-lived, however, as the characteristic proceeds through a dramatic decline, halted only by a respite during the simulations of the European and Mass Producers. When comparing the mass production and 'leaner' production sides of the evolutionary scheme, it can be seen that the characteristic is of significantly more value on the mass production side than for the leaner organisations. The characteristic, although in sharp decline, loses, on average, 9 units on the mass production side and 20 units on the leaner production side and fails altogether with the Agile Producer.

Figure 8.21. The value performance of character-state 13 throughout the simulations



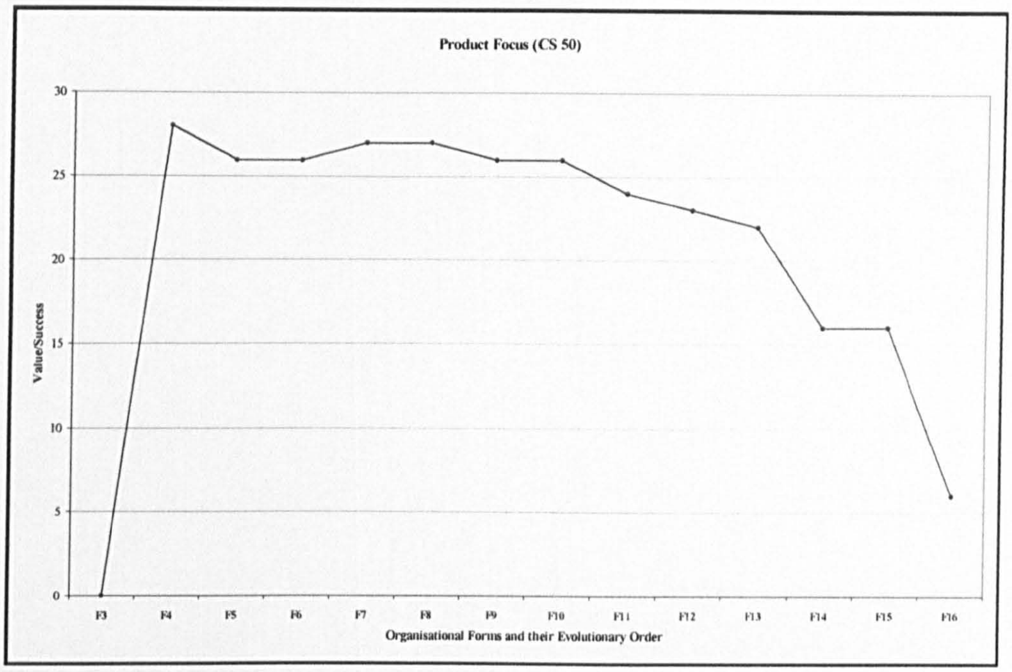
Character-state 16, socialisation training, is introduced in the simulation of the Skilled, Large-Scale Producer and, as can be seen from figure 8.22, was very successful keeping its value during the next simulation. As the simulation moves into the mass production side of the evolutionary scheme, the characteristic dropped in value somewhat but performed consistently at this level (i.e. between 14 and 17 units of value). In contrast, the characteristic did not perform as well in the leaner side of the scheme dropping initially down to 8 value units for the Just in Time-, Flexible Manufacturing- and Toyota Production Systems. The characteristic's value declined further for both the Lean and Agile Producers but in contrast to the previously discussed characteristic still survived the full evolution ending with 5 units of value.

Figure 8.22. The value performance of character-state 16 throughout the simulations



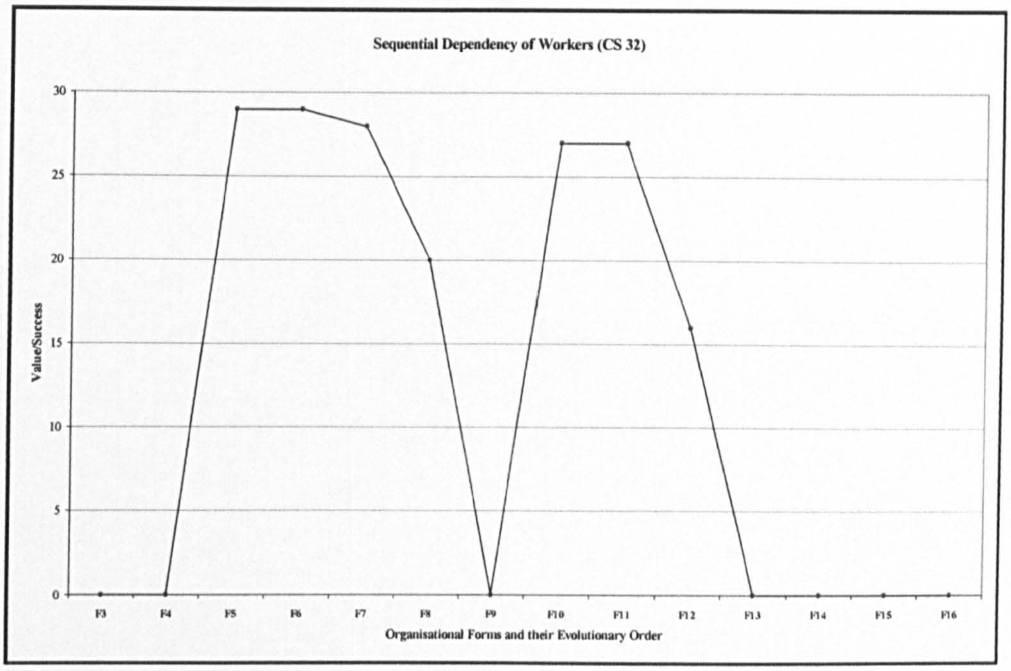
The fate of character-state 50, product focus, was very interesting particularly when contrasting with the fates of all the previously discussed characteristics. Figure 8.23 shows that after the characteristic's introduction during the simulation of the Neocraft system it performed very successfully reaching a stabilised value of approximately 28 units of value. Throughout the proceeding simulations the characteristic kept its value at around 26-7 units until the last organisation on the mass production side of the evolutionary scheme where it dropped to 24 units, the first time it went below 26 units of value. The characteristic was still successful having a very influential role in both the Just in Time- and Flexible Manufacturing Systems having a value of 23 and 22 units, respectively. When compared to all the other characteristics that make up the next two simulations (i.e. that define the Toyota Production System and Lean Producer), the characteristic still performed relatively successfully at 16 value units; only character-states 1 and 50 have similar values. However, its performance declined drastically during the simulation of the Agile Producer dropping to approximately 6 units. The characteristic's decline during the last three simulations may be a logical reaction to the three types of organisation's focus on a diverse product base and mass customisation.

Figure 8.23. The value performance of character-state 50 throughout the simulations



Character-state 32, sequential dependency of workers, had a very interesting evolutionary history during the simulations. The characteristic was introduced at the beginning of the simulation of the Skilled, Large-Scale Producer and instantly performed very successfully reaching a stabilised value score of 29 units (see figure 8.24). The characteristic maintained this score during the next simulation of the Large-Scale Producer and only dropped 1 value unit throughout the simulation of the Mass Producer (Fordism). It was evident that in the simulation of the Modern Mass Producer that the characteristic lost 8 units of value, but overall was still at a very healthy value of 20 units. The interesting part was when the Pseudo Lean Producer was simulated and the characteristic dramatically lost all its value and disappeared from the organisation. However, as the European Mass Producer does not evolve from the Pseudo Lean Producer, but from the Large-Scale Producer, the characteristic was present from the beginning of the simulation and again performed successfully for both European and the Intensive Mass Producer ending both simulations with a value of 22 units. The characteristic declined in value again during the simulation of the Just in Time System but still ended with a fairly healthy value of 16 units.

Figure 8.24. The value performance of character-state 32 throughout the simulations

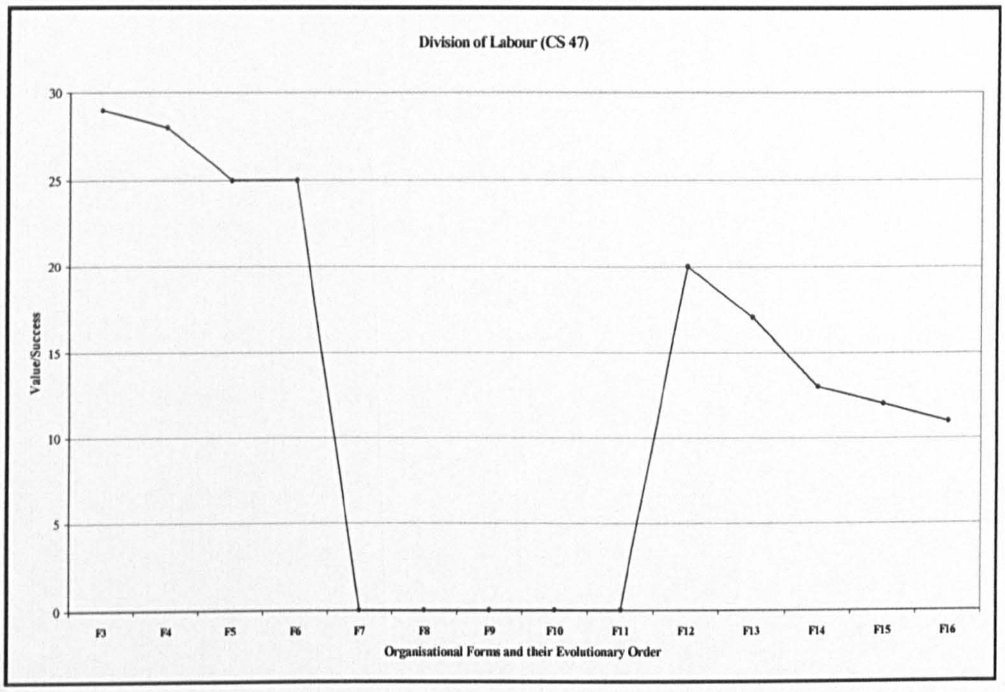


The characteristic failed for the second time with the simulation of the Flexible Manufacturing System and as such took no further part in the evolutionary run. The complete failure of the characteristic from previously healthy values is an interesting phenomenon as, according to the original automotive assembly plant cladogram of figure 8.1, the character-state is a precursor to both Large-Scale Producers and to all the mass and leaner producing organisations.

What is consistent, however, is the introduction of potentially conflicting characteristics in both the simulations of the Pseudo Lean Producer and the Flexible Manufacturing System. The characteristics in question include CS 24, flexible, multifunctional workforce, and CS 33, line balancing, both of which arguably conflict with CS 32, sequential dependency of workers. The introduction of CS 38, manufacturing cells, during the Flexible Manufacturing System has also the potential to conflict. Perhaps all these characteristics in concert over-powered the influential role held by CS 32.

As can be seen from figure 8.25, CS 47, division of labour, also had an interesting history in the simulated evolutionary run. After being introduced in the first simulation, the characteristic performed very successfully and ended with a stabilised value score of 29 units. The characteristic lost 1 value unit during the next simulation and a further 3 units in the third simulation maintaining this score of 25 units during the fourth simulation. The characteristic, however, lost all its value during the simulation of the Mass Producer (Fordism), and as all remaining mass-producing organisations evolve from the Mass Producer (Fordism), the characteristic took no further part until the Just in Time System which evolves from the Large Scale Producer.

Figure 8.25. The value performance of character-state 47 throughout the simulations



During this latter simulation of the Just in Time System, the character-state lost 5 units but the value was still healthy and influential at 20 units. Although, the characteristic lost a total of 9 units during the next four simulations it still survived and ended the evolutionary run with a stabilised value score of 11. This value score of 11, at this point in the evolutionary run and when compared to the other character-states at this stage, was also an arguably healthy score beaten only by character-states 1 and 51 both with values of 16 units (see table 8.7).

The failure of CS 47 during the simulation of the Mass Producer (Fordism) is a little puzzling as 'division of labour' is a classic defining attribute in the literature (e.g. Womack et al, 1990) of the typical mass producing company and introduced by

Henry Ford himself. Possible reasons for this very unexpected result may be due to the methodology and/or data collection design and procedure, such as sampling problems (i.e. general manufacturers instead of automotive manufacturers) and misinterpretation at the questionnaire stage (both discussed further in the next chapter). Another reason may be due to missing information in the original cladogram or missing characteristics that have synergies with CS 47, which, if present, would help the survival of CS 47. Another reason may be due to weighting (discussed in the next chapter).

8.3. Individual Simulations of the Organisational Forms

In contrast to the full evolutionary simulation procedure, individual simulations of the organisational forms launch each of the respective characteristics of the original manufacturing cladistics research by McCarthy et al (1997), all at equal values of 5 units. With the full evolutionary simulation procedure, if a characteristic failed in one simulation it did not have another opportunity in the next simulation if the following organisation evolved from the previous organisation.

For example, CS 47 failed during the simulation of the Mass Producer (Fordism) in the full evolutionary simulation procedure and therefore took no further part in the next four simulations representing the remainder of the mass producers. The individual simulation procedure therefore gives characteristics that failed in previous simulations another chance to integrate itself into the next respective simulation. It also prevents the influence of previously dominating characteristics either singularly or in synergetic bundles.

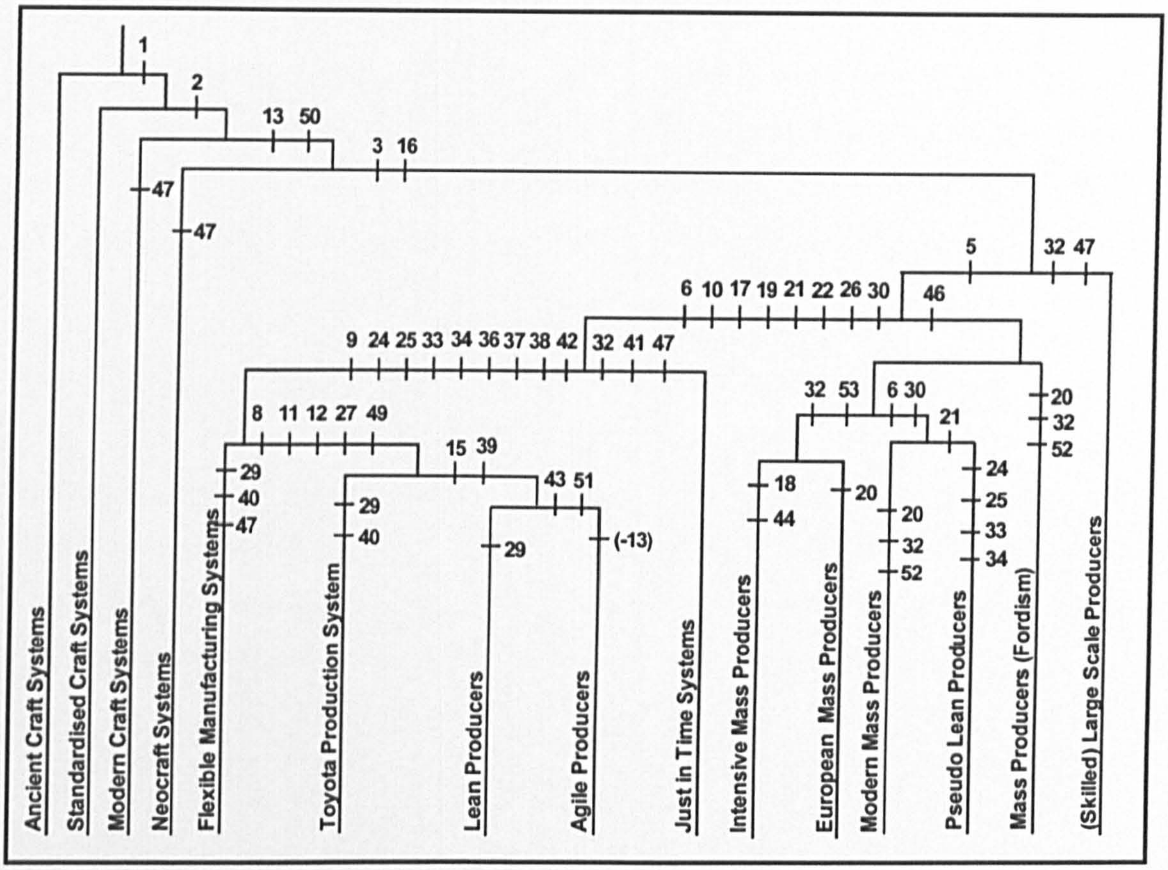
Table 8.6 summarises the results of the individual simulations of the organisational forms. Although the individual simulations are very similar to the full evolutionary simulations there are some very interesting and important differences concerning character-states 29, 40, 47 and 52 (e.g. compare table 8.3 which summarises the full evolutionary simulation results with table 8.6).

Table 8.6. Table of simulation results for the organisational forms and their characteristics launched individually at 5 value units

	Organisational Form	**Failed Characteristics**	**Remaining Characteristics**	**Total Time**
1	Ancient Craft Systems	(Not Simulated)		
2	Standardised Craft Systems	(Not Simulated)	1	
3	Modern Craft Systems	None	1, 2, 47	10,000
4	Neocraft Systems	48	1, 2, 13, 47, 50	10,000
5	Skilled Large Scale Producers	48	1, 2, 3, 13, 16, 32, 47, 50	15,000
6	Large Scale Producers	4, 48	1, 2, 3, 13, 16, 32, 47, 50	10,000
7	Mass Producers (Fordism)	4, 14, 47, 48	1, 2, 3, 5, 13, 16, 20, 32, 46, 50, 52	10,000
8	Modern Mass Producers	4, 14, 47, 48	1, 2, 3, 5, 6, 13, 16, 20, 30, 32, 46, 50, 52	15,000
9	Pseudo Lean Producers	4, 7, 14, 20, 32, 47, 48, 52	1, 2, 3, 5, 6, 13, 16, 21, 24, 25, 30, 33, 34, 46, 50	12,000
10	European Mass Producers	4, 14, 45, 47, 48, 52	1, 2, 3, 5, 13, 16, 20, 32, 46, 50, 53	15,000
11	Intensive Mass Producers	4, 14, 45, 47, 48, 52	1, 2, 3, 5, 13, 16, 18, 32, 44, 46, 50, 53	15,000
12	Just In Time Systems	4, 28, 31, 48	1, 2, 3, 5, 6, 10, 13, 16, 17, 19, 21, 22, 26, 30, 32, 41, 47, 50	15,000
13	Flexible Manufacturing Systems	4, 7, 28, 31, 32, 41, 48	1, 2, 3, 5, 6, 9, 10, 13, 16, 17, 19, 21, 22, 24, 25, 26, 29, 30, 33, 34, 36, 37, 38, 40, 42, 47, 50	15,000
14	Toyota Production System	4, 7, 28, 31, 32, 35, 41, 47, 48	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 13, 16, 17, 19, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 40, 42, 49, 50	15,000
15	Lean Producers	4, 7, 23, 28, 31, 32, 35, 40, 41, 47, 48	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 13, 15, 16, 17, 19, 21, 22, 24, 25, 26, 27, 29, 30, 33, 34, 36, 37, 38, 39, 42, 49, 50	25,000
16	Agile Producers	4, 7, 13, 23, 28, 29, 31, 32, 35, 40, 41, 47, 48	1, 2, 3, 5, 6, 8, 9, 10, 11, 12, 15, 16, 17, 19, 21, 22, 24, 25, 26, 27, 30, 33, 34, 36, 37, 38, 39, 42, 43, 49, 50, 51	35,000

The resulting cladogram from these results is very similar to the cladogram produced from the full evolutionary run (see figure 8.26 when compared to figure 8.16). During the full evolutionary run CS 52 failed immediately after its introduction in the Mass Producer (Fordism) and consequently played no further part. During these simulations, however, CS 52 did survive in the Mass Producer (Fordism) as well as the Modern Mass Producer (nonetheless it did fail during the simulations of the European and Intensive Mass Producers). Why it failed in the evolutionary run and not in the individual run must be due to previous values of the former procedure (the primary difference between the two procedures). With the full evolutionary run, the values of the ancestral characteristics remain the same from the last stable solution (in this case the Large-Scale Producer), whereas with the individual simulations, all relevant characteristics are launched with equal values (in this case 5 units). This difference of course has huge implications as different initial conditions create different potential trajectories. Returning to the cladogram seen in figure 8.26, this means that CS 52 is labelled on both the Mass Producer (Fordism) and the Modern Mass Producer.

Figure 8.26. Amended automotive assembly plant cladogram according to individual simulations



Apart from this characteristic there are no other differences in the structure of the organisations of the first ten simulations. However, it can be seen that the individual simulations of the Pseudo Lean Producers, both the European and Intensive Mass Producers, and the Just in Time system take far less time to reach the stable solution than in the full evolutionary run (compare table 8.3 with table 8.6).

Character-state 47 also has a different role in this cladogram compared to the cladogram of the original work and the full evolutionary run. In the full evolutionary run, the characteristic didn't feature in any of the organisations on the mass production side of the evolutionary scheme. With these simulations, the characteristic also doesn't feature in any of the mass-producing organisations but also doesn't survive in three of the five 'leaner' producing organisations persisting only in the Just in Time- and Flexible Manufacturing Systems. As CS 29, first emerging in the Flexible Manufacturing System, fails in the Agile Producer the position on the cladogram therefore changes to reflect this. Interestingly, CS 40 which can be seen to emerge in the Flexible Manufacturing System in the original manufacturing cladistics work (see figure 8.1), fails altogether in the full evolutionary run, but survives in two organisations in the individual simulation runs – the Flexible Manufacturing and Toyota Production Systems. This again highlights the difference of the two simulation approaches (i.e. the full evolutionary run and the individual simulation runs), where different initial conditions create different stable solutions. Both approaches are thus viable when validating basic manufacturing cladistics research and provide different insights and perspectives into the evolutionary history.

8.4. Random Organisational Innovations and Evolution

This results section reports on simulations of organisations, all starting from the Standardised Craft System (i.e. with only CS 1, standardisation of parts), that randomly introduce additional character-states from the available 53 characteristics. These simulations represent organisational innovation albeit in a haphazard fashion. The model has the ability to launch characteristics with different orders through seeding. Therefore different evolutionary trajectories and histories can be explored. The results of one such simulation are analysed in detail. After this analysis a further four simulations at their end state are presented and the similarities with, and differences between each innovative run as well as with previous simulations (in section 8.1) are highlighted.

The model is calibrated in the following way to address this type of simulation. Firstly the model is set to run to a total time of 100,499 time units. The simulation begins with CS 1 starting with 2 units of value. Thereafter, a characteristic is chosen and introduced at random (according to the starting seed which allocates a certain random run) at every 500 time units. This enables the launch of 200 character-states. Obviously some characteristics that are already present are re-introduced at 2 value units. This can represent both an initial loss of commitment to that particular character-state if the original value was above 2 units of value or a reinvestment of commitment if the original value was below 2 units. In addition, the re-introduction of character-states that were already present could lead to the disruption of the organisation for a short duration and could affect the domination of certain characteristics or bundles of synergetic characteristics changing the whole evolutionary trajectory. With 200 character-states introduced throughout the simulation there is a high likelihood that all available characteristics are introduced at some point during the run.

Figure 8.27 shows the frequency of the character-state introductions during the first full innovative run, which had the random seed of 1. There are several initial observations to be made. The first is that all but two character-states (15 and 53) were introduced. Nineteen character-states were introduced 5 or more times with CS 1 being introduced ten times and character-states 28 and 39 introduced eight times. Four character-states (11, 33, 37 and 40) were introduced only once.

Figure 8.27. Frequency of character-state introductions throughout the innovation run

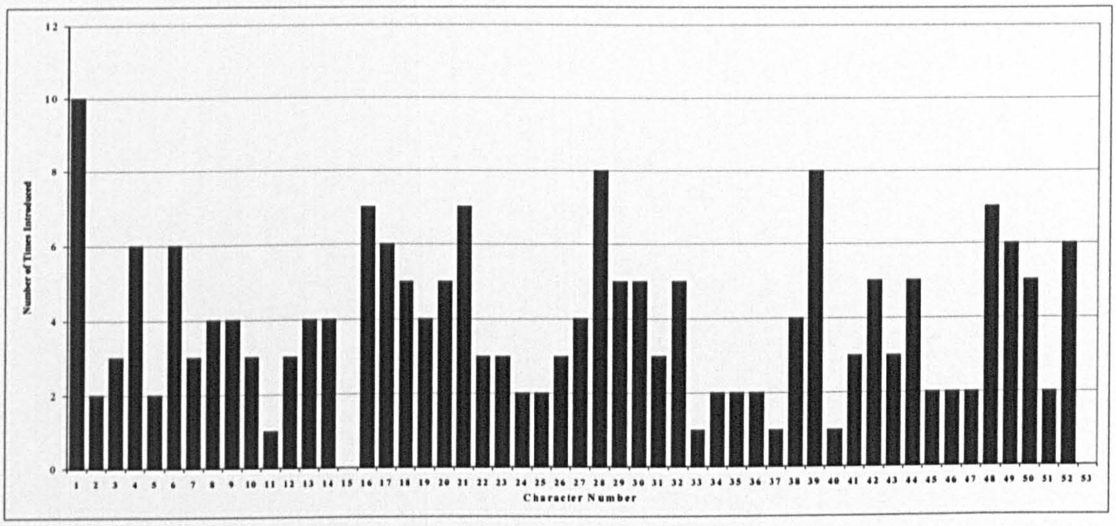


Table 8.7 shows the time sequence as well as the introduction and failure of the different character-states during the first simulation. The table is also divided into periods of change and periods of stasis (in terms of no change to the organisational form). The periods of stasis are highlighted in grey. The stasis periods refer to the actual structure, and although the values of character-states are changing continually, the actual structure of the organisation remains the same. There are essentially two different periods of stasis. One represents the introduction of an already present character-state. The other represents the introduction and failure of the same

character-state during the 500 time units. A characteristic has to survive the initial introduction period (of 500 time units) to represent significant change.

Table 8.7. Table of time sequence and corresponding innovations (character-state introduction) and failures during the first innovation run (seed 1)

Time	CS I	CS F	Time	CS I	CS F	Time	CS I	CS F	Time	CS I	CS F
0	1		25500	42		50500	52	52	75500	17	
500	13		26000	24		51000	17		76000	9	
1000	14		26500	49		51500	17		76500	4	4
1500	5		27000	44		52000	16		77000	49	
2000	23		27500	10		52500	18		77500	9	
2500	27		28000	47	47	53000	2		78000	27	
3000	48		28500	13		53500	2		78500	50	
3500	30		29000	26		54000	33		79000	52	52
4000	21		29500	49		54500	45	45	79500	39	
4500	32		30000	28		55000	36		80000	48	48
5000	35	14	30500	17	13, 28	55500	52	52	80500	21	
5500	17	32	31000	1		56000	39	36	81000	25	
6000	38		31500	39		56500	31		81500	10	
6500	16		32000	6		57000	3	31	82000	32	
7000	4	4	32500	40		57500	3		82500	19	32
7500	16		33000	43		58000	20	20	83000	12	
8000	28		33500	10		58500	18		83500	29	
8500	8	28	34000	49	40	59000	16		84000	16	35
9000	32		34500	31		59500	16		84500	18	
9500	1		35000	13		60000	23		85000	6	
10000	31	32	35500	50		60500	48	48	85500	42	
10500	50		36000	12		61000	25	23	86000	50	
11000	4	4	36500	1		61500	43		86500	18	
11500	51		37000	52	52	62000	26		87000	48	48
12000	29		37500	23	13, 31	62500	32		87500	14	14
12500	21	29	38000	20	20	63000	4	4	88000	29	
13000	30		38500	8		63500	29	32	88500	8	
13500	37		39000	1	23	64000	29		89000	41	
14000	26		39500	44		64500	48	48	89500	30	
14500	4	4	40000	6		65000	49		90000	36	
15000	28		40500	49		65500	8		90500	7	
15500	38	28	41000	28		66000	30		91000	31	
16000	21		41500	18	28	66500	38		91500	32	7, 31
16500	6		42000	46	46	67000	28		92000	39	
17000	28		42500	28		67500	1	28	92500	17	32
17500	1	28	43000	6	28	68000	52	52	93000	5	
18000	12		43500	21		68500	42		93500	1	
18500	39		44000	27		69000	51		94000	22	
19000	7		44500	42		69500	35		94500	9	
19500	4	4, 48	45000	11		70000	41		95000	39	
20000	14	7, 14	45500	22		70500	44	41	95500	20	20
20500	20	20	46000	21		71000	6		96000	7	
21000	20	20	46500	27		71500	48	48	96500	34	
21500	39		47000	22		72000	19	29	97000	24	7
22000	14	14	47500	43		72500	38		97500	3	
22500	44		48000	39		73000	34		98000	44	
23000	13		48500	28		73500	19		98500	19	
23500	1		49000	21	28	74000	16		99000	46	46
24000	47		49500	45	45	74500	42		99500	9	
24500	1		50000	52	52	75000	48	48	100000	41	41
25000	50	13									

There are several interesting points to be made. The first is that the beginning of the simulation was characterised by change and the take-up of innovations (the first column of the table) whereas the end of the simulation was characterised by stasis (the last column of the table). After 5,000 time units the first character-state, CS 14, suppliers selected primarily on price, fails after having been introduced 4,000 time units earlier. It is interesting to note that most of the characteristics that fail, fail after a relatively short period of time.

There are several characteristics that when introduced struggled for a while and then fail. These include character-states 7, reduction of lot size, 28, 100% inspection/sampling, 32, sequential dependency of workers, and 40, ABC costing, which all survived between 500 and 1,500 time units. Some characteristics (i.e. character-states 4, 14, 20, 41, 45, 46, 47, 48 and 52) fail immediately, i.e. within the same time period of introduction. However, there are qualifications. Although this was absolutely true of character-states 4, reduction of lot size, 20, multiple subcontracting, 45, immigrant workforce, 46, dedicated automation, and 52, dependence on written rules, the other character-states had some success albeit short-lived.

For example, CS 14, suppliers selected on price, lasted approximately 4,000 time units. When it was first introduced it reached a value of 22 but with the introductions of the next 5 character-states it lost value (i.e. losing on average 1.5 units of value with each introduction) but after each loss of value regained some stability. However, it was with the introduction of CS 21, quality systems, that the value of CS 14 dramatically fell from 14 value units to its utter failure. This is quite logical as quality systems would be more suited to the policy of TQM sourcing (CS 27), which was introduced at T=2,500, rather than suppliers selected on price (CS 14).

Character-state 47, division of labour, is an interesting case as it was introduced to the organisation relatively late during the run at T=24,000. After a slow start it managed to reach a value of 16 units. During the next few innovations its value fluctuated between 10 and 14 value units but eventually reached some stability at 10 value units. However, the commitment was challenged, through re-introduction, at T= 28,000 at which point it disappeared rapidly from the organisation. In this case the only plausible explanation, after analysing the simulation, is that the sudden lack of 'confidence' or commitment to the character-state causes a terminal instability. The character-state is not re-introduced again throughout the simulation.

Another example is with CS 48, employees are system tools, which survived for 16,500 time units. In this instance, CS 48 succeeded for a while reaching a maximum value of 30. This value was maintained up until T=11,000 but then promptly lost 12 units of value with the introduction of CS 50, product focus, and then even more so with CS 51, parallel processing. However, CS 48 again maintained its value of 18 units up until the introduction of CS 39, concurrent engineering, where CS 48 rapidly lost all its value and disappeared from the organisation.

It appears that the combined effect of character-states 51 and 39 is the sole reason for the demise of CS 48 and makes sense as these new practices (in terms of the evolutionary history) are more suited to character-state 49, employees are system developers rather than system tools (i.e. CS 48). Importantly however, CS 49 had not yet been introduced, but when it was introduced the characteristic flourished and did not once disappear from the system even when its commitment, through re-introduction, was questioned 5 times during the run.

Character-state 41, excess capacity, had an interesting impact. When it was first introduced at T=70,000 it failed after the next innovation (i.e. after T=70,500). However, it was then introduced again at T=89,000 and managed to survive and flourish for a while (reaching 11 units of value) until it was introduced again, as the last innovation, at T=100,000 and then promptly disappeared from the organisation.

Through analysing the simulation there are no obvious reasons for why this characteristic flourished then failed other than when it was introduced the second time it must have been involved in a synergetic bundle that helped build its value to the organisation. Once commitment was reduced the synergy must have been lost leading to the characteristic's demise.

There are also characteristics that were introduced and do well for a good length of time but then fail after the commitment is challenged. For example, character-state 13, large volume production, which was first introduced at T=500, managed to survive 22,500 time units. The characteristic performed well initially reaching the maximum value of 30. It performed very well with its value not dropping below 16 units for the first 18,000 time units. However, when CS 39, concurrent engineering, was introduced its value dropped to approximately 10 units but still managed to reach a stable position in the organisation.

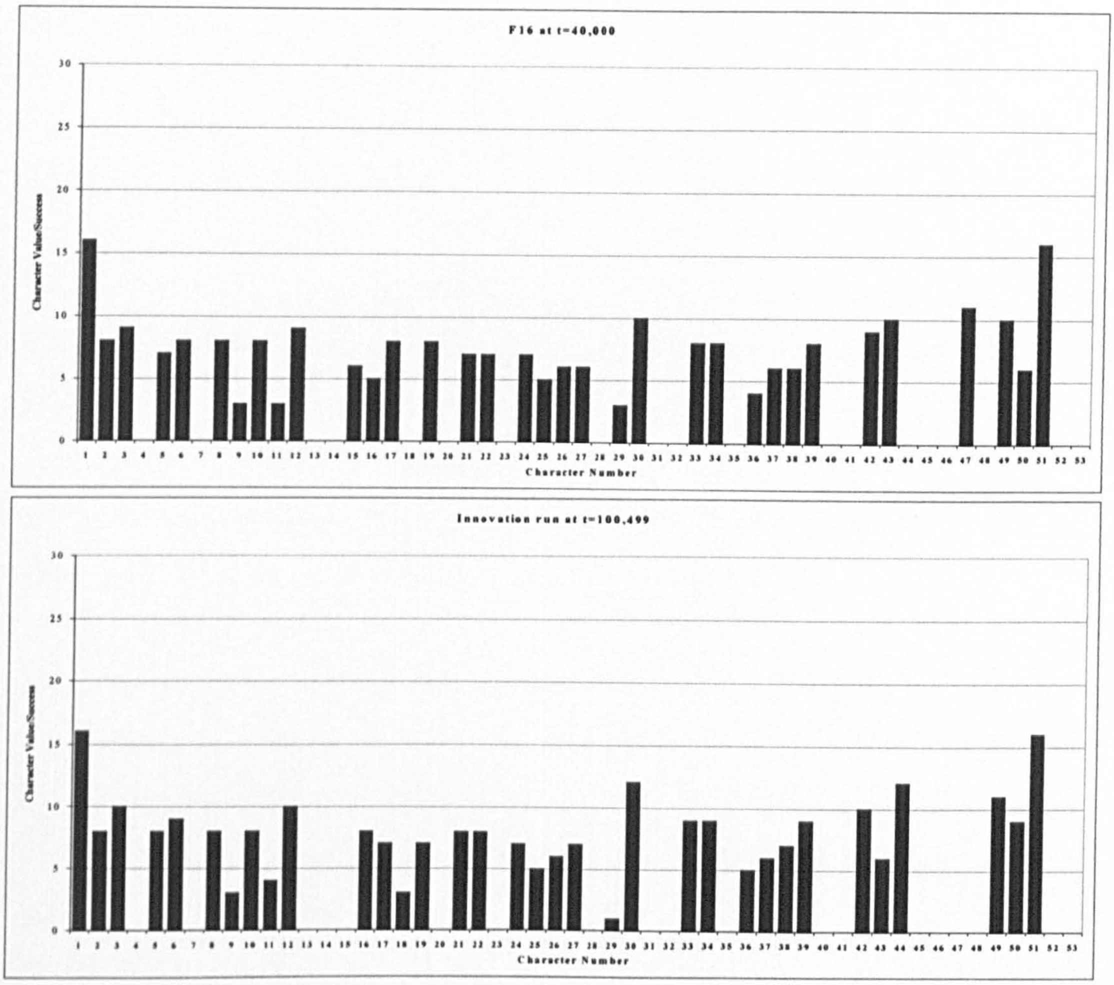
However, at T=23,000 its position was challenged as it was reintroduced. The characteristic could not recover its importance to the organisation and gradually lost its value during the following 2,000 time units. It was then re-introduced two more times but again failed after only 2,000 time units. This scenario was also typical of character-states 23, open book policy with suppliers, and 31, individual error correction, in that they were introduced early on in the simulation, survived for a good time but then were reintroduced and failed.

In contrast CS 29, U-shape layout, was first introduced at T=12,000 but failed after only 500 time units. The characteristic was again introduced at T=63,500 and T=64,000 and survived up until T=72,000 but never exceeded its starting value. The characteristic was introduced twice again at T=83,500 and T=88,000 and although its value dropped to 1 unit it maintained its position in the organisation until the end of the simulation.

This scenario was also repeated with CS 36, groups Vs teams. Again this character-state was introduced at T=55,000 but then failed after only 500 time units. However, it was then re-introduced at T=90,000 and more than doubled its introduction value ending the simulation with a value of 5 units. Through analysing the simulation there appears to be no obvious reason why the characteristic failed on its first attempt but then prospered on its second chance.

One very interesting observation is that the final organisation that emerges from the first innovation run has a very close resemblance to the Agile Producer simulated in the section 8.1 of this chapter. Figure 8.28 compares the end result of the innovation run with the stable solution of the Agile Producer.

Figure 8.28. A comparison between the stable solution of the Agile Producer and the end result of the innovation run (seed 1)



Twenty-seven characteristics share approximately the same value. That is, 10 characteristics (i.e. character states 1, 2, 8, 9, 10, 24, 25, 26, 37 and 51) have approximately the same value and 17 characteristics (i.e. character-states 4, 7, 13, 14, 20, 23, 28, 31, 32, 35, 40, 41, 45, 46, 48, 52 and 53) are not present in both organisations (although CS 53 did not get launched). Fourteen of the characteristics (i.e. character-states 3, 5, 6, 11, 12, 21, 22, 27, 33, 34, 38, 39, 42, and 49) during the innovation run had gained approximately 1 unit of value when compared to the stable solution of the Agile Producer. One characteristic (i.e. CS 30) gained 2 value units and two characteristics (i.e. character-states 16 and 50) gained 3 units. Three characteristics (i.e. character-states 17, 19 and 36), when compared to the stable solution of the Agile Producer, dropped 1 unit of value; one characteristic (i.e. CS 29) lost 2 value units; and another characteristic (i.e. CS 43) dropped four value units.

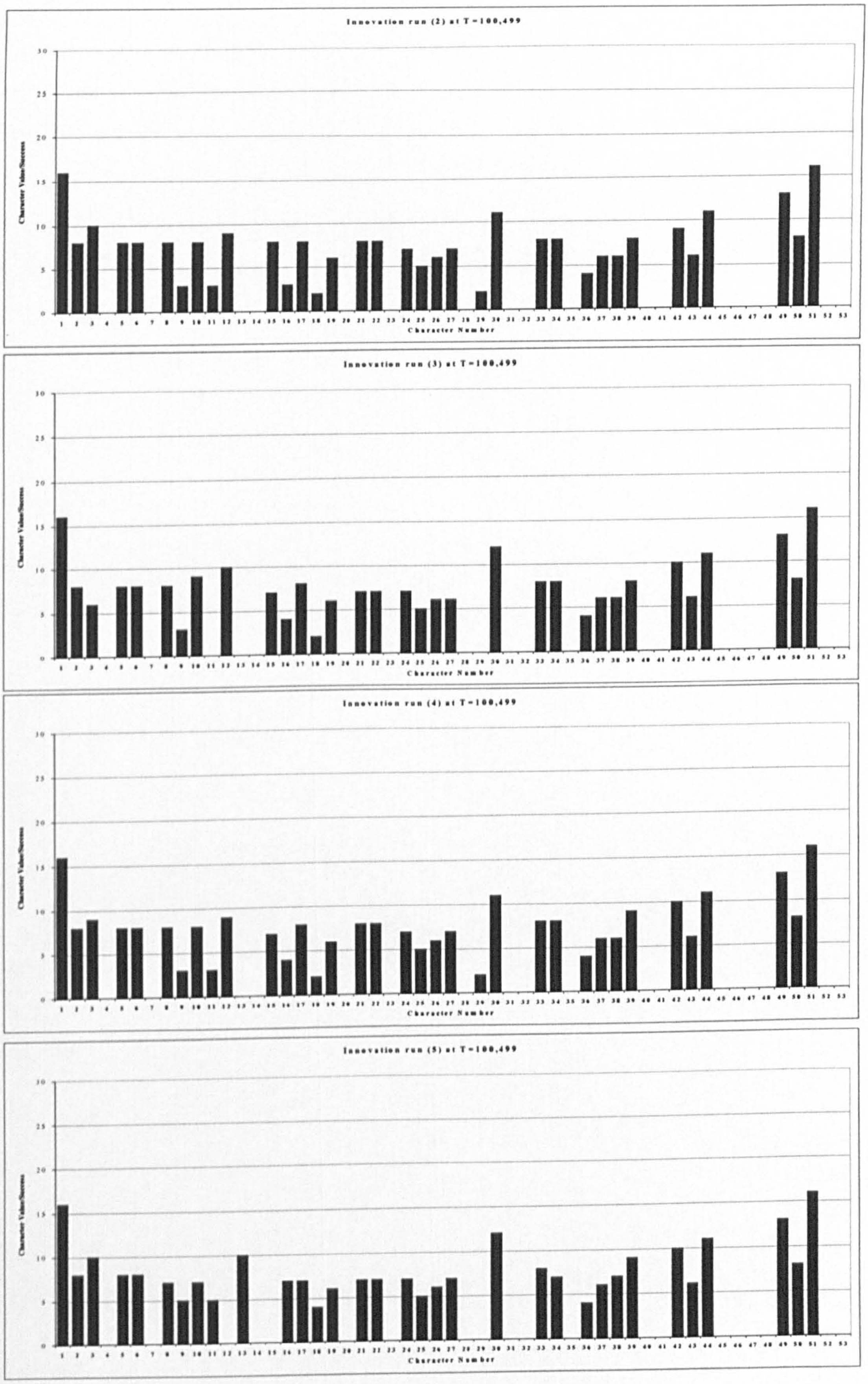
There are also two characteristics missing from the innovation run that are present in the stable solution of the Agile Producer which are CS 15, exchange of workers with suppliers, which didn't get launched, and CS 47, division of labour, which failed to make an impact after having two introductions during the innovation run. Interestingly there were also two extra characteristics, i.e. CS 18, product range reduction, and CS 44, insourcing, which managed to survive the simulation.

Figure 8.29 shows the end results of a further four innovation runs seeded consecutively 2 to 5, i.e. all having different character-state launch sequences. All four of these runs launched all 53 character-states at some point during the simulations. It can be seen that all four end results of the different innovation runs highly resemble the stable solution of the Agile Producer simulated in section 8.1 of the chapter. There are, however, some important differences.

It can be seen that three out of the four end results contained CS 15. In addition CS 18 again managed to survive all four of the innovation runs suggesting that it is a very compatible characteristic for this organisation. Character-state 47 failed to make an impact again in all four of the innovation runs which is very interesting as the characteristic is very prominent, with a value of 11 units, in the stable solution of the Agile Producer.

During the innovation run seeded 3, CS 11, employee innovation prizes, failed to survive the simulation, as did CS 29, U-shape layout, which also failed during the innovation run seeded 5. During this last innovation run (seeded 5) CS 12, job rotation, also failed while CS 13, large volume production, managed for the first time, in all innovation run simulations, to succeed and flourish reaching a value of 10 units.

Figure 8.29. The end results of four other innovation runs (seeds 2-5)



8.5. Simulating Organisational Transformations

This set of simulations investigated change and transformation of a particular organisation. Therefore the aim was to launch an organisational form at its most stable solution, in this case the *Modern Mass Producer*, and then introduce new characteristics. There were two main objectives of this aim. The first was to relate the results to issues such as those surrounding decision-making uncertainty and specific barriers to the introduction of new practices. The second objective was to demonstrate the exploratory capacity of the model, particularly when evolving new organisational structure. An example of the process of simulation for the Modern Mass Producer (MMP) can be seen in figure 8.30. As with the individual simulation procedure, all characteristics of the MMP were launched with a starting value of 5 (see figure 8.30 at Time=50).

Figure 8.30. Simulation of the stabilisation of character interactions of the Modern Mass Producer (MMP)

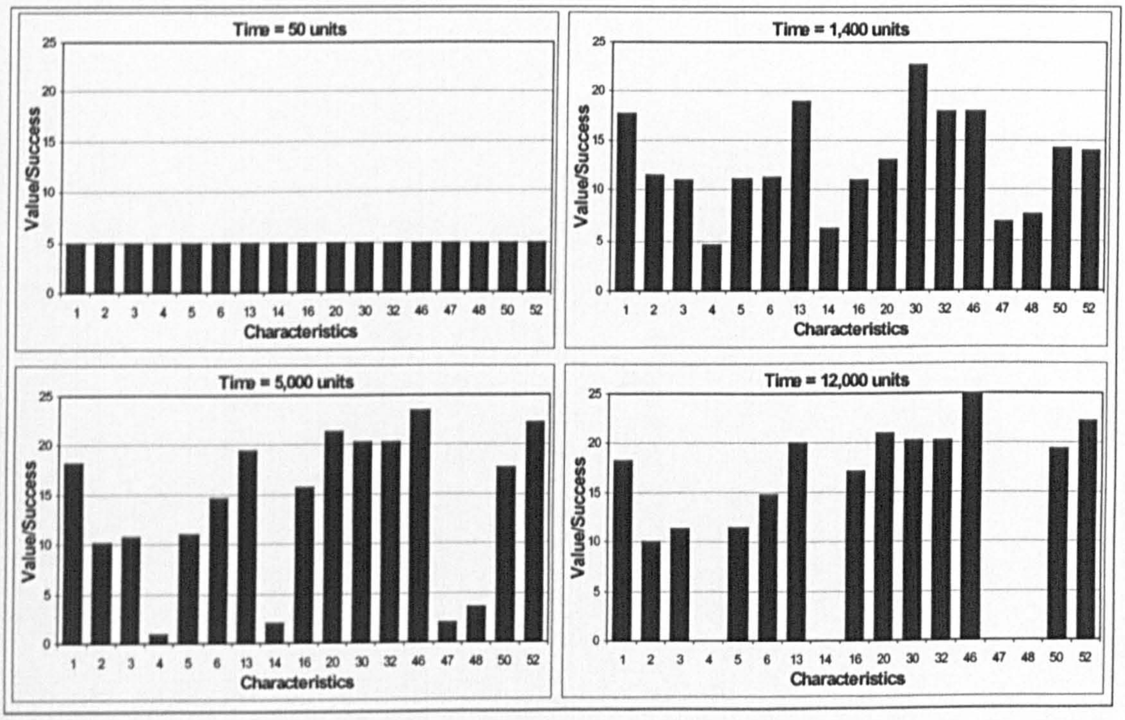


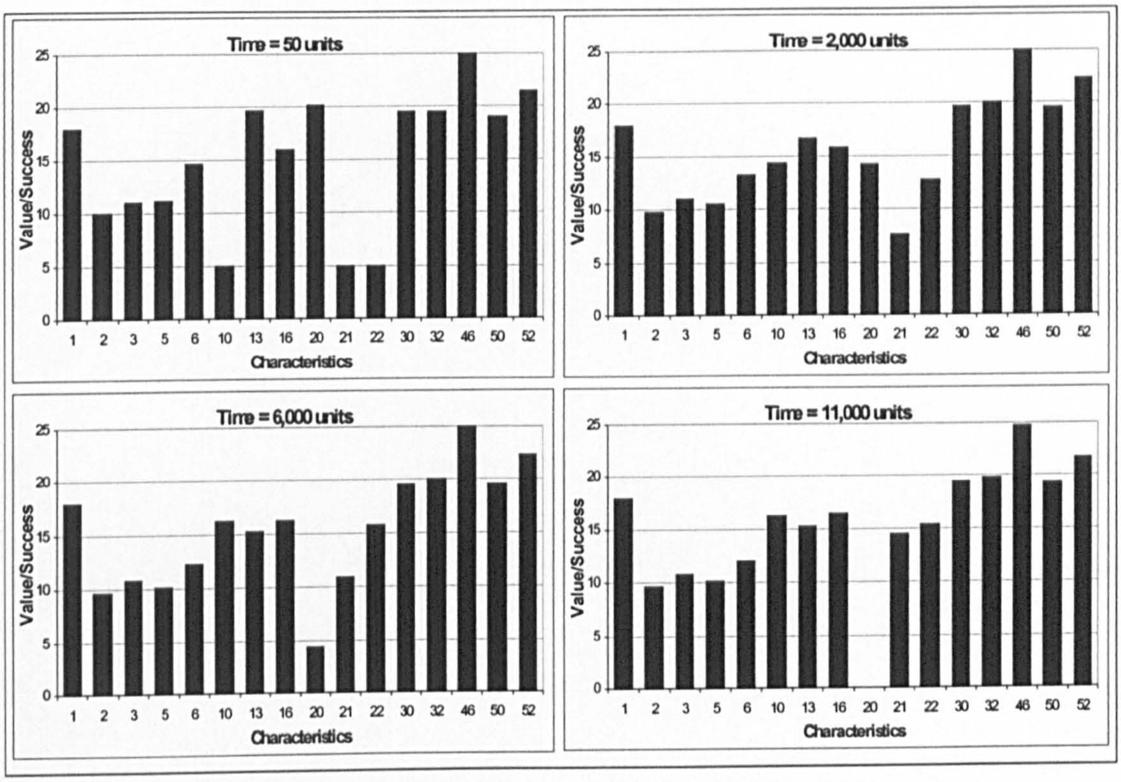
Figure 8.30 at Time=1,400, a relatively short period of time, shows character-states 4, reduction of craft skills, 14, suppliers selected on price, 47, division of labour, and 48, employees are treated as system tools, failed to make an impact from the beginning due to the accumulative interactions of all the other characteristics. This was

consistent with the findings presented in table 8.6. The demise of these characteristics is depicted in figure 8.30 at Time=5,000 and Time=12,000. Figure 8.30 at Time=1,400 shows that the influential characteristics at the beginning of the evolutionary run were CS 1, standardisation of parts, CS 13, large volume production, CS 30, preventive maintenance, CS 32, a sequential dependency of workers, and CS 46, dedicated automation. Figure 8.30 at Time=5,000 and Time=12,000, shows that with the demise of the unstable characteristics, character-states 16, socialisation training, 20, multiple subcontracting, 50, product focus, and 52, a dependence on written rules, all increased in value.

The aim of the study was to identify potential obstacles when introducing new technologies or practices to existing manufacturing organisation. The *Modern Mass Producer* (MMP) was the experimental case study (see figure 8.30). The model was run with all the organisation's defining characteristics until a stable solution was found. In this case, it was without character-states 4, 14, 47 and 48 (figure 8.30 at Time=12,000). The value for each characteristic was noted and re-launched at these values. New characteristics were then introduced. The first area investigated was practices relating to quality, that is character-states 10, quality circles, 21, quality systems, and 22, quality philosophy.

Firstly, CS 21 was introduced singularly with a starting value of 5 and had an immediate effect on CS 20 which became unstable and failed. One finding that was interesting, and continues from the results and observations in section 8.4 of this chapter, concerned the commitment behind introducing quality systems. If quality systems (CS 21) was introduced with little commitment (e.g. a starting value of 2), the characteristic took a much longer time period to establish itself than if introduced with a stronger commitment (e.g. with a value of 5). The three quality characteristics were then introduced as a package. When this new structure was launched (see figure 8.31) CS 13 suffers slightly dropping down from a value of 18 to a value of 13 (see figure 8.31 at Time=50 and Time=6,000). In addition to this, CS 20 failed completely (see figure 8.31). The combined effect of all three quality characteristics, however, had an overall stronger value at the stable solution (see figure 8.31 at Time=11,000).

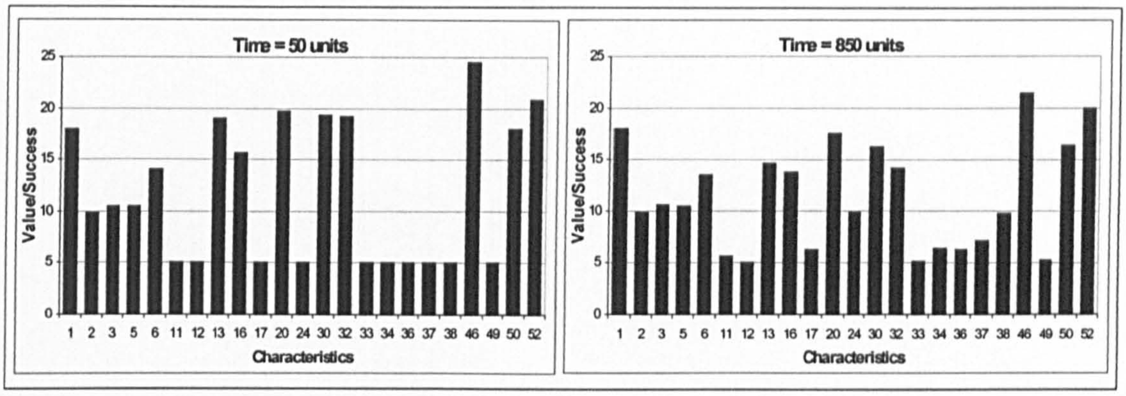
Figure 8.31. Simulation of the introduction of quality characteristics to the MMP configuration



Having identified that multiple subcontracting reacted negatively with the new practices the procedure was then repeated for characteristics relating to the workforce policies of the MMP organisation (see figures 8.32 and 8.33). This included introducing characteristics 11, employee innovation prizes, 12, job rotation, 17, proactive training programmes, 24, flexible multifunctional workforce, 33, line balancing, 34, team policy, 36, team ethic, 37, job enrichment, 38, manufacturing cells, and 49, employees as system developers.

These characteristics were introduced as a bundle with surprising consequences (see figure 8.32). First of all, there was an initial shock to the system, where most characteristics lost some value and became temporarily unstable (see figure 8.32).

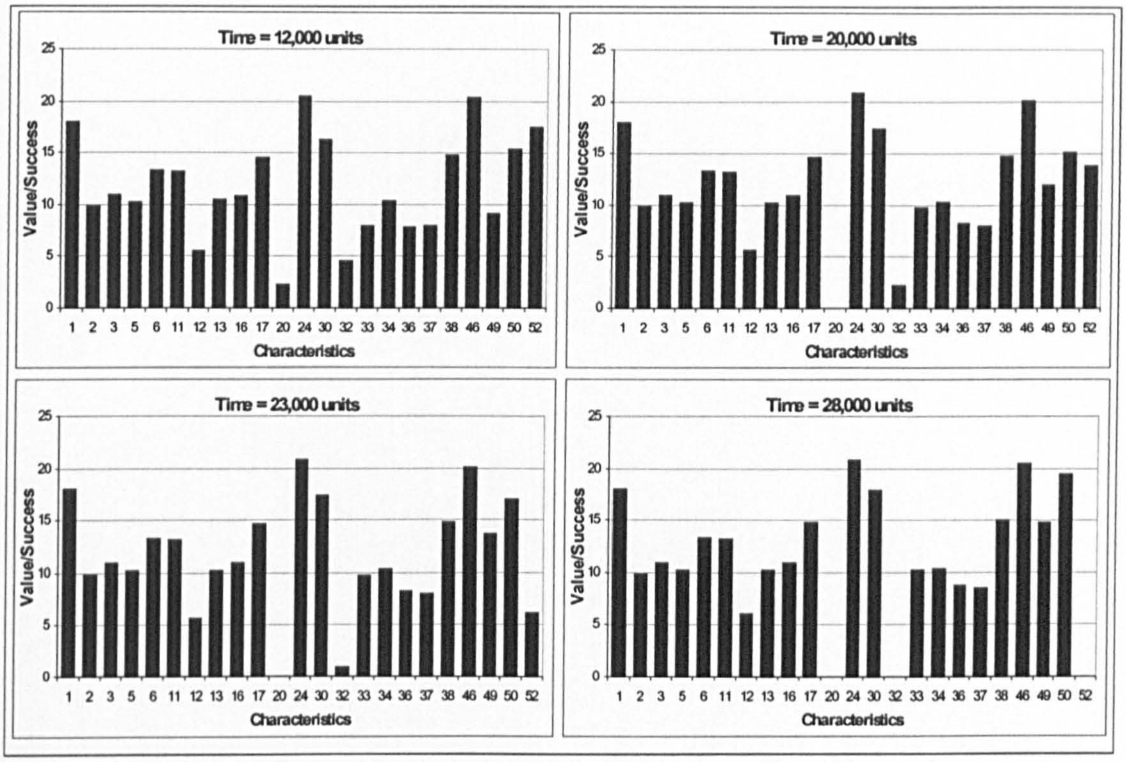
Figure 8.32. Simulation of the introduction of workforce characteristics to the MMP configuration with initial system shock



It took the system a relatively long time to recover (see figure 8.33 at Time=12,000), after which most characteristics stabilised including the new introductions. This perhaps reflects real situations when a package of new practices (in this case 10 new policies) challenges the rest of the organisational structure, having effects on both productivity and the internal workings and philosophy of the organisation. Three characteristics (i.e. character-states 20, 32 and 52) did not recover from the instability and disappeared from the system (see figure 8.33 at Time=12,000 and Time=20,000).

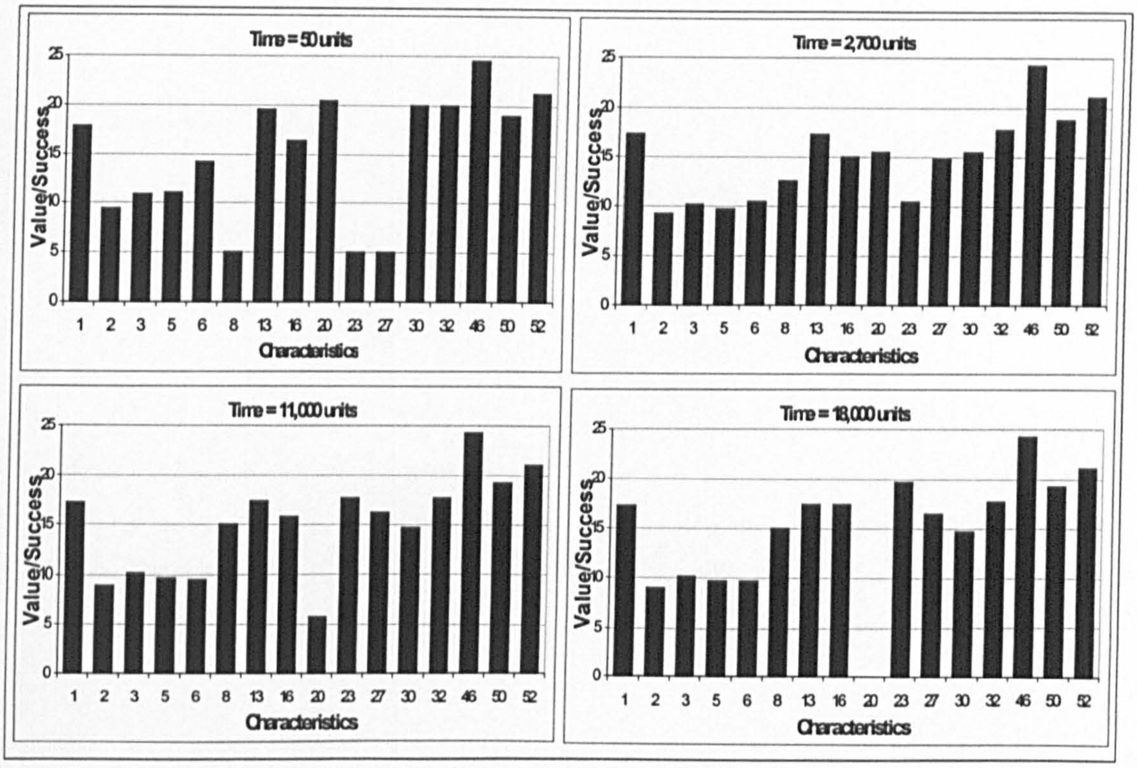
The disappearance of all three of these characteristics is perhaps logical as they counteract many of the new practices introduced. Another interesting finding is that when the model approached a stable solution (see figure 8.33 at Time=20,000), CS 52 suddenly and rapidly decreased in value and soon disappeared (see figure 8.33 at Time=23,000 and Time=28,000). This finding indicates that the interactions of technologies and practices can occur over long time periods and that some characteristics have certain thresholds that when crossed, can have critical implications for the rest of the organisation. In this instance, it appears that the new workforce policies needed time to embed themselves in the organisation before they could influence other parts of the organisation. This demonstrates the potential of the model when looking at problems with longer time horizons.

Figure 8.33. Simulation of the introduction of workforce characteristics to the MMP configuration (continued)



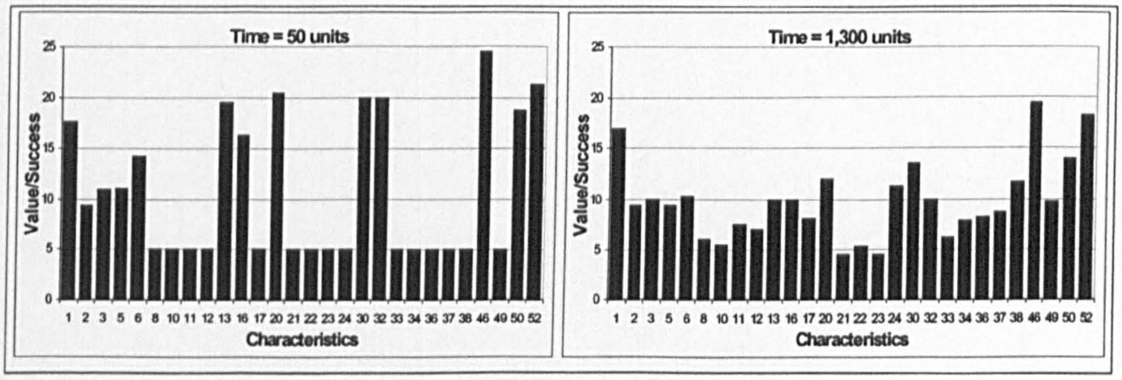
Another area of exploration concerned policies regarding the supply side of the organisation (see figure 8.34). The characteristics concerned were 8, pull procurement planning, 23, an open book policy with suppliers and a sharing of costs and profits, and 27, TQM sourcing where suppliers are selected on the basis of quality. When all three of the characteristics were introduced together, the whole organisation was affected, with small decreases in most of the values of the characteristics. Nonetheless, the system recovered apart from multiple subcontracting which again failed. Characteristics 6, pull production system, and 30, preventive maintenance also had significant reductions in value (by 4 units) although were still influential in the overall organisation (see figure 8.34). These findings are a little puzzling, as the new practices/policies are not directly related to the character-states that failed. However, as the model takes into account the indirect interactions of all characteristics all at once, subtle influences and synergetic bundles of characteristics, as these findings indicate, are often very important in an organisational setting. This is one of the main advantages of the model – the exploration of all potential consequences that seem in some instances logical and in others illogical, totally unrelated and surprising. This suggests that not all benefits and risks can be calculated beforehand whilst also highlighting the limited capacity of foresight in certain situations.

Figure 8.34. Simulation of the introduction of supplier characteristics to the MMP configuration



One final area explored with the MMP organisation was the introduction of all these characteristic packages, policies relating to quality, the suppliers and the workforce (15 new character-states), that would create an altogether new organisational form (see figures 8.35 and 8.36).

Figure 8.35. Simulation of the introduction of quality, workforce and supplier characteristics to the MMP configuration



As can be seen from figure 8.35, the introduction of the 15 new character-states produced quite a shock to the system. From previous results, this was perhaps expected, but again indicates problems when introducing new characteristic bundles. Characteristics that were particularly affected but recovered some stability, were character-states 6, 13, 16, 30, 46, and 50. The strongest characteristics after the initial shock (see figure 8.35 at Time=1300) were character-states 1, 46 and 52. Figure 8.36 depicts the demise of the unstable characteristics.

Figure 8.36. Simulation of the introduction of quality, workforce and supplier characteristics to the MMP configuration (continued)

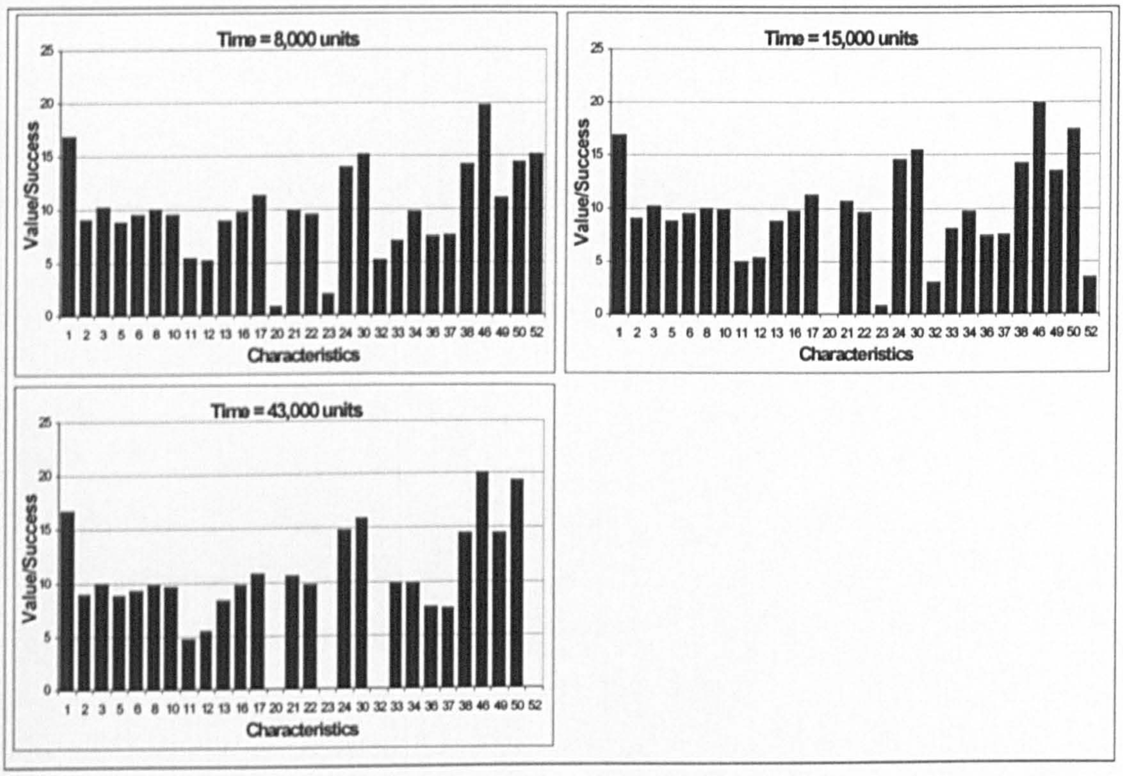


Figure 8.36 at Time=8,000 shows the first two characteristics to disappear, character-states 20 and 23. The disappearance of multiple subcontracting (CS 20) is perhaps expected in the light of previous results, but the disappearance of open book policy with suppliers (CS 23) is surprising as this characteristic was successful when introduced both on its own and in combination with other supplier policies. There is no obvious reason why this character-state failed this time, other than the subtle indirect interactions with other practices and policies discussed above. Figure 8.36 at Time=8,000 also shows that whilst CS 32 is in decline, CS 52 still had a healthy

value. Figure 8.36 at Time=15,000 shows that CS 52 again fails after a relatively long time period. When comparing figure 8.35 at Time=50 and figure 8.36 at Time=43,000 it can be seen that the only original characteristics that were hardly affected were character-states 1, 2, 3, and 5. One final observation (see figure 8.36 at Time=43,000) is that out of the surviving 24 character-states, only 7 characteristics could be said to have healthy values in terms of the importance to the organisation (character-states 1, 24, 30, 38, 46, 49, and 50).

8.6. Chapter Summary

This chapter was concerned with the application of the evolutionary model to the cladistic evolution of automotive assembly plants. The first set of results was concerned with the evolution of the industry according to the evolutionary history detailed by McCarthy et al (1997). An alternative or amended cladogram was presented as one of the main outcomes. The next set of results highlighted the different perspectives that the evolutionary model can produce, in this instance the tracking of performance and fitness of individual characteristics throughout the full evolutionary run.

The third set of results highlighted an alternative simulation procedure in which all organisations and their respective characteristics are launched as new organisations where all character-states are treated with equal value/commitment. Although the end results were very similar to the full evolutionary run, there were important differences particularly involving character-states that failed during the full evolutionary run but were given other opportunities to integrate themselves. A second amended cladogram was produced through these simulations.

The fourth set of results was interested with the innovation process. There were several interesting insights particularly concerning character-state failures, commitment issues, domineering characteristics and synergetic bundles of characteristics. The final set of results to be presented was an investigation into the issues concerned with organisational change and transformations. The model demonstrated its usefulness in providing important insights into the decision-making processes, risk and unpredictability in management and evolving new organisational forms through the simulation of compatible characteristics. The significance of these results as well as conclusions and recommendations for further research are discussed in more depth in the next chapter.

CHAPTER 9 – MODELLING MANUFACTURING EVOLUTION: DISCUSSION, CONCLUSIONS AND FURTHER RESEARCH

9. Introduction

The results of the simulations of the evolutionary model of the cladistic evolution of automotive assembly plants presented in chapter 8 have provided some very interesting as well as important observations and insights. The chapter begins with a discussion of the significance of the results (as well as potential problems with this and previous research) and then how this relates, in terms of application, to the problems and issues currently facing manufacturers. Further research areas that build upon this platform of research are then highlighted. The potential research directions include using the new evolutionary framework to a) help with the transition to more sustainable manufacturing, b) help solve the problem of evolution when modelling industrial ecosystems, and c) explore the notion of bounded rationality in the processes of management decision-making when change is contemplated.

9.1. Significance of Results

The first section of the results in chapter 8 followed the evolution of the assembly plants according to the manufacturing cladistics research of McCarthy et al (1997). The procedure involved taking the values of the previous simulation (in terms of the evolutionary history) and introducing the new characteristics that distinguishes the new organisation to the already stable solution of the previous organisation. The first important observation was that many of the characteristics during these simulations failed. The reasons behind these failures are discussed in more detail in the next section. The failure of these characteristics however, led to a re-think and design of the cladistic history of the industry. Firstly, eleven characteristics failed completely and as such are not stable enough, according to the evolutionary model, to be used as descriptors of the organisations. This limits the 'dictionary' of description for the evolutionary history to just 42 character-states (instead of 53).

Importantly, the 16 organisational forms detailed in the original work were reduced to 15 organisations during the full evolutionary simulations. This was because character-state 4, reduction of craft skills, failed to make an impact. This was the only characteristic that distinguished the Large Scale Producer from the Skilled, Large Scale Producer. What was interesting, however, was that when CS 4 was introduced it shocked the rest of the organisation with most of the other characteristics initially losing heavily in terms of value. Shocks to the organisation, which were more pronounced in the section of results that dealt with organisational transformations, were usually attributed to the introduction of several characteristics and not just one. It therefore appears that CS 4 had a lot of negative influence, which when introduced not only impacted negatively on other character-states temporarily, but also led to its own rapid downfall.

However, it is obvious that reduction of craft skills is indeed an important descriptor of the organisations under study (according to the original cladogram the character-state is present in the next 10 organisations), which leads to the speculation that more descriptors are needed, that would form a synergetic bundle of character-states and the survival of the unstable characteristic. This also applies to the other 10 characteristics that failed to make an impact. The distribution (and emergence) of certain characteristics was also changed leading to fundamental changes in how we think the industry evolved. This would indicate that a more thorough investigation into the evolution of the industry is needed to clarify the differences between the original manufacturing cladistics work and this research. However, as is discussed in the next section, the data that was collected was from a general manufacturing background and not from automotive manufacturers and thus have certain limitations.

Another important observation that must be kept in mind for both major organisational transformations and for new-start ups in a mature industry is that as the simulations proceeded through the evolutionary order, the amount of time taken increased considerably to reach a stable solution. For example the time taken for stabilisation in the first three simulations was 10,000 time units whereas the last three simulations took 40,000 time units.

The full evolutionary simulations also demonstrated the model's usefulness in terms of longer time horizons. For example, the failure of CS 28, 100% inspection/sampling, and CS 31, individual error correction, during the simulation of the Just in Time System, took a considerable amount of time. In previous simulations the failures were fairly rapid and represented a total inability to invade the system. However, this simulation suggested that the character-state failures were not a question of invasion but really of increasing synergy between complimentary character-states that gradually but increasingly conflicted with the two characteristics.

It is also interesting to note that in the early simulations involving only a few characteristics that the values of each character-state were fairly high with a few even reaching the maximum value of 30 units during the simulations. However, as the organisations became more complicated in terms of the number of characteristics and the relationships involved, the values of character-states were quite modest. This can be seen when contrasting the first few of the simulations (including several of the mass producing organisations), which had many characteristics around and above the 20 units of value mark, to the last few simulations starting with the Just in Time System. The effect is more pronounced in the last three simulations where all of the characteristics had values not more than 16 units with the majority under 10 value units. This effect arguably mirrors the fact that in more complicated systems the dependency on character-states is more diffuse, and that there is a high degree of interdependency and synergy between characteristic bundles. In addition, the organisation is not relying heavily on just a few character-states to survive. With less complicated organisations the value assigned to characteristics is perhaps over-emphasised and justifiably so, as the organisation's survival is heavily reliant on just a few technologies and practices.

The final observation to be made is that of the fourteen organisations simulated only one (i.e. the Modern Craft System) survived with its defining characteristics. A further three organisations (i.e. the Skilled, Large Scale Producer, the Modern Mass Producer and the Intensive Mass Producer) survived with the introduction of their distinguishing character-states, that is, no characteristics failed during the simulation but some of their defining characteristics failed in previous simulations. This has important implications for either the study design and methodology in this thesis or for the previous research conducted by McCarthy et al (1997). Further research is needed to clarify this issue.

Section 8.2 of the results highlighted that the evolutionary model may also be used to gain a different perspective through studying the performance or fitness of individual characteristics throughout the simulations of the full evolutionary run. These results, in addition to tracking performance in terms of fitness with respect to each individual organisation, also permit the analysis of performance in the context of other characteristics. This method may provide additional insight into the evolution of both the characteristics and the enveloping organisation. It highlights in what types of organisations and with what other character-states, certain types of characteristics are more likely to succeed (or fail).

The point made above concerning the reduced value in the latter part of the full evolutionary run simulation procedure is made very apparent with these results. With all characteristics (i.e. 9 character-states) that were tracked the value either gradually or rapidly declined. For example, CS 1, standardisation of parts, one of the more successful character-states, was stabilised initially at 24 units of value but declined to 16 value units at the end of the simulation procedure. More dramatically, CS 13, large volume production, began with 19 value units and declined rapidly until its demise in the last simulation.

In two of the cases the characteristics failed altogether but were then introduced again later in the procedure. One characteristic, CS 32, sequential dependency of workers, was introduced during the Skilled, Large Scale Producer and performed very well for the next three simulations never dropping below 20 value units. However, with the simulation of the Pseudo Lean Producer the characteristic failed rapidly. The characteristic was then re-introduced (in line with the original cladogram) during the simulation of the European Mass Producer and again performed vary well reaching a value of 27 units which was maintained for the next simulation. Although the characteristic dropped value during the simulation of the Just in Time System it still remained healthy at 16 units of value. The characteristic, however, failed rapidly again during the simulation of the Flexible Manufacturing System and as such took no further part. It is interesting to note that, unlike the rest of the mass-producing organisations as well the Just in Time System, the Pseudo Lean Producer shares several characteristics with the Flexible Manufacturing System including character states 7, 24, 25, 33 and 35. This is an excellent demonstration of the power of synergetic bundles of characteristics (in this case character-states 24, 33 and 35) over-powering an already dominant characteristic (i.e. CS 32).

The other characteristic, CS 47, division of labour, performed very well in the first four simulations never dropping below 25 value units. However, in the next simulation, for the first mass producer, it failed completely and therefore took no further part in the mass-producing organisations. It re-emerged in the leaner producing organisations and although it didn't reach its initial value it relatively flourished in the remainder of organisations. This is a very perplexing result as the division of labour is regarded in the literature (Womack et al, 1990) as almost synonymous with mass production and introduced by Henry Ford himself. There is no obvious reason why this happened and clearly further research is needed to solve this puzzle.

An alternative technique and procedure with which to analyse the evolution of organisations was presented section 8.3 of the results. With this procedure the organisation and their respective character-states were all launched as if it was a new organisation and each character-state had equal weighting. Although the results were on the whole very similar there were several important differences to the full evolutionary run. The main difference was that in the full evolutionary run if a character-state failed early in the evolution it often did not have another opportunity to re-emerge or integrate in further simulations. With the individual simulations characteristics could be tested again in organisations next in the evolutionary history. Four characteristics were found to have entirely different roles in the history and as such different positions in the cladogram. The differences however, did not fundamentally differ from the full evolutionary run but nonetheless aids the investigation particularly in terms of change and transformations.

This alternative technique, combined with the full evolutionary procedure, enables a more in-depth look of why characteristics perform as they do from simulation to simulation. For example, in a number of cases character states failed in the full evolutionary simulations but not in the individual simulations and vice versa. With the individual simulations synergetic bundles are not influential at the beginning of the simulation. Therefore why characteristics perform better or worse (with or without the synergies) can be more accurately isolated and root causes explored.

Section 8.4 of the results was an investigation into the innovation process and an exploration of the actual model. The first observation is that, as expected, the early stages of the innovation process and organisational evolution was characterised by take-up of technologies/practices and continual change. This observation was consistent with all five of the different innovation runs. However, as the remaining untried characteristics became more limited in number, the model began re-introducing character-states, which represented an internal review of the particular characteristic and, in most cases, a challenge of commitment. Therefore the middle stages of the innovation run was characterised by a selection process where the least fit character-states were weeded out. The final stages of the innovation run was characterised by a stabilisation of the organisation where new technologies/practices had a very limited chance of invading. This was partly due to the domination of certain character-states and the presence of very influential synergetic bundles of characteristics.

It is interesting to note that the character-states that more often than not failed (i.e. character-states 4, 7, 14, 20, 28, 32, 40, 41, 45, 47, 48 and 52) also failed during both the full evolutionary simulations and the individual simulations, demonstrating that the evolutionary model has a high degree of consistency. However, there were qualitatively different types of failure involved. One of the more common types of failure was characterised by an introduction and then a rapid loss of all its value within a very short period of time (e.g. often before the next innovation).

Another type of characteristic failure happened again after its introduction but this time over a period of on average 4-5 innovations. The characteristic itself didn't appear to highly conflict with the rest of the organisation as the loss of value was very slow. In this instance it appears that the characteristic's presence heightened a moderately conflicting synergetic bundle so that as the characteristic lost value the bundle gained value. Another type of characteristic failure occurred when the commitment to the characteristic was challenged and occurred with several characteristics. With this type of failure the characteristic's value before its re-introduction was very healthy and enjoyed an influential position in the organisation. However, when it was re-introduced it failed to make an impact and either rapidly or slowly disappeared from the system. This has important implications for questions of commitment particularly when introducing new and innovative technologies and practices.

A final observation from these results is that after five innovation runs all with different (and random) sequences of character-state introduction, all the end states highly resembled the Agile Producer. This suggests that the Agile Producer organisation is a powerful structural attractor according to the character-state interactivity and the evolutionary model. However, this raises some concerns for this and previous research. For example, it would be expected that other organisations would equally provide a high degree of attraction and that the mass-producing organisations, given their history and dominance in manufacturing, would offer a powerful alternative to the leaner producing organisations. More research is required and arguably more characteristics that define the mass-producing organisations need to be added in order to truly represent the importance of mass-production in evolutionary history.

The last section of the results relates to one of the main aims cited by McCarthy et al (1997) of manufacturing cladistics and concerns organisational change and transformation. The aim of these results was to demonstrate the usefulness of this approach to problems such as those encountered when introducing new technologies, practices and policies to an existing organisation. The experimental case study was the Modern Mass Producer as it is a fairly recent organisation (with many still existing today) and because there were still many characteristics that were potentially new to this structure.

Three specific areas, that is, characteristics relating to quality, the workforce and the suppliers, were explored. One of the first observations again concerned the issue of commitment. It was seen that if a characteristic, in this case quality systems, was introduced with little commitment, the time taken for it to establish itself was much longer than if there was a greater initial commitment.

Another important observation seen in many of the simulations was that there was an initial shock to the organisation causing a considerable instability. The more characteristics introduced produced more of a shock to the system. This is quite logical as when a set of new practices, policies and/or technologies are introduced there is going to be initial confusion as the organisation gets used to the change involved. As the new characteristics challenge old ways of working this potentially affects both productivity and the culture and philosophy of the organisation. As the simulations reflect, with any change, be it minor or major, time is needed to get a degree of stability.

With the new introductions, some of the old characteristics (as well as some introductory characteristics) failed. In most instances there appeared to be a plausible explanation, as the new characteristic is a more efficient or effective practice than the failed characteristic. However, there were some surprising failures, where characteristics, having no significant relationship with the introductory character-states, failed for no apparent reason. In these instances, the failure is arguably due to the subtle interactions between all characteristics that sometimes result in illogical events.

In addition to subtle interactions, the effects of synergetic bundles of characteristics that span the entire organisation also appear to play a significant role in these events. For example, the quality policies introduced caused the failure of multiple subcontracting whilst also negatively impacting large volume production. This raises the question: Would the effect on large volume production have been anticipated beforehand with the introduction of quality policies. The model also gives some indication of the unpredictability, risk and uncertainty in decision-making. The simulation also demonstrates its potential for identifying problem areas and exploring possible solutions.

During these simulations the model also demonstrated its capacity to explore problems over longer time horizons. This was seen in the simulation that introduced the workforce policies. Although two characteristics failed within the typical period of time, character-state 52, dependence on written rules, failed just as the simulation looked like it was reaching a stable solution. This raises questions not only over the subtle interactions and synergetic bundles of characteristics but also concerning critical thresholds that when breached have devastating consequences for the characteristic and possibly the organisation. It appears that in this simulation the new workforce policies needed time to form their relationships and synergies with the other characteristics before challenging the status of character-state 52. This again highlights and supports the notion of inherent uncertainty and unpredictability in the decision-making process.

9.2. Reasons for Character-State Failure

The failure of the 11 characteristics in the full evolutionary run is very interesting and has important implications for both this study and the original manufacturing cladistics research on the automotive assembly plant. The failure of these characteristics may be due to one or more of several potential reasons. The first and most obvious reason could be the fault of the questionnaire design. One possibility may be due to misinterpretation of the statements and questions on the questionnaire. For example, 'reduction of craft skills' is a lack of a characteristic and may have been misinterpreted.

In the original automotive cladogram it can be seen that this characteristic is essential for most of the organisational forms. In addition, there may also be a question of weighting the characteristics. For example, CS 1, standardisation of parts, is far more important than CS 11, employee innovation prizes, or CS 12, job rotation. There are also questions such as timing of introduction, i.e. some characteristics would be introduced earlier than others and some may also be precursors, for example, CS 5, automation, may be thought of as a precursor to flexible (CS 42) and agile automation (CS 43).

The second reason that certain characteristics failed could be due to the sampling procedure. The sample, highlighted in the methodology (chapter 7), was from a general manufacturing background, including manufacturers from metal products to footwear and leather goods to medical goods. This could have important bearings on the simulations and limits many of the conclusions made concerning the previous research by McCarthy et al (1997). If the evolutionary systems methodology were to be used as a verification tool, then the data that would need to be collected would have to be drawn from a sample of the automotive manufacturers' population.

Nonetheless, it also must be noted that many of the manufacturing systems as well as the practices and technologies in the original research on the automotive industry are also very common in general manufacturing, with only a few systems and technologies specific to the automotive industry. In addition, this research was more concerned with the actual synthesis of manufacturing cladistics and evolutionary systems modelling and should be treated as a pilot or feasibility study. However, this sampling problem must be a seen as a potential candidate for the failure of characteristics in the simulations.

Another possibility may be due to certain characteristics having 'bad press' in the media, which may influence opinions on certain interactions. A good possible example of this is the CS 47, division of labour. This of course is essential for all manufacturing organisations (and in most other social systems) with the exception of the first two craft systems where one craftsman typically produced the end product. Similarly, there is also a question of psychological barriers, in terms of perceptions and biased opinions, to certain characteristics.

For example, CS 14, suppliers selected primarily on price, is not as popular or as manufacturing-friendly as CS 23, open book policy with suppliers and the sharing of cost (noting, of course, that this character-state also failed). However, it may be a necessity for many manufacturers and possibly for most of the manufacturers who responded to the questionnaire. In other words, respondents may not like the policy/practice and indicate that it is negative, but may be nonetheless essential for their operations. The same is true with *overemphasis* particularly for those practices and policies that are currently in management fashion. Typical examples of these have been job rotation, job enrichment, quality philosophy and even lean production.

The characteristics that failed are as follows:

CS 4: Reduction of craft skills
CS 7: Reduction of lot size
CS 14: Suppliers selected primarily on price

CS 23: Open book policy with suppliers

CS 28: 100% inspection/sampling

CS 31: Individual error correction; products are not re-routed to a special fixing station

CS 35: Toyota verification of assembly line

CS 40: ABC costing

CS 45: Immigrant workforce

CS 48: Employees are system tools and simply operate machines

CS 52: Dependence on written rules; unwillingness to challenge rules as the economic order of quantity.

There are several potential reasons for these failures in terms of the respondents' biased perceptions. The first observation is that 5 of these characteristics (i.e. character-states 4, 14, 45, 48 and 52) arguably create a negative impression and implies taking liberties and a lack of trust with the workforce and in the supply chain. Several of the other characteristics are derived from the Japanese manufacturers (e.g. character-states 23, 28, 31 and 35) and their failure may be due in part to cultural differences in the way the British manufacture.

A final speculative reason for the failure of these characteristics is due to the cladogram itself along with the chosen characteristics. The failure of these character-states may be due purely to missing organisational attributes that if present act in concert with the failed character-states, i.e. a synergetic bundle, ensuring their survival. This argument is supported, if it is incorrect to assume that of all the automotive assembly plants in business that the total defining characteristics comes to just 53. In the real world the number of potential characteristics, for example, different technologies, practices, policies, company-philosophies, company-cultures, management structures, and strategies, are in the hundreds if not thousands.

This is further highlighted in the original cladogram by the fact that the first organisational form, the Ancient Craft System, has no defining characteristics. The skills involved, their marketing strategy, their technologies, and the company's management although perhaps simple, are just ignored. With this in mind, the evolutionary modelling techniques and the simulations reported may be utilised as a verification tool for constructing cladograms. This could ensure that essential characteristics are present in the cladogram, that problem organisational forms and characteristics are identified and further investigated, and that solutions are stable.

In addition, further research is needed to address issues relating to the weighting of some of the more important characteristics, a clearer and more understandable description of character-states in the questionnaire, a chronology of character introduction in reality, and a possible inclusion of a verification period were experts in industry and academia validate data.

9.3. A Tool for Decision-Making

One of the main problems studied in this investigation was the consequence of introducing new practices and as such the decisions behind these introductions. The first issue identified was the management's view (and possibly the workforce's view) of some of the characteristics. Psychological barriers (in terms of perceptions and biases), which may manifest in organisational culture, have an important bearing on the success of any new characteristic. The psychological barrier in this case, was deemed to cause several of the characteristics to fail in all types of organisations. Some of these characteristics were seen in the original automotive cladogram as essential prerequisites to most of the organisational forms. Similarly, as was highlighted with CS 21, quality systems, the initial commitment of the organisation is very important in the success of any new characteristic. Commitment is an issue not only for quality policies (e.g. Goh, 2000) but also for all technologies and practices.

The model demonstrated how new practices may emerge and how they interact with other characteristics. With these interactions successes and failures are quite often logical in terms of one characteristic replacing a similar characteristic, but are also sometimes illogical and quite surprising indicative of a high degree of unpredictability. This unpredictability highlights the limited capacity of foresight, and in some aspects, precaution. It is these scenarios that the indirect and somewhat subtle interactions influence the fates of unrelated character-states. It was demonstrated that innovations behind organisational transformations, in different spheres in the organisation, for example, quality, supplier and workforce policies, can have unexpected and disastrous consequences on either production or the overall internal consistency or harmony of the organisation.

The model, through simulating these processes, stable solutions, and potential consequences, both in the short- and long-term, can be an aid to management in decision-making, in terms of reducing uncertainty. Fully exploring the consequences could also have an overall impact in reducing, for example, the timescales involved in major organisational transformation. In one of the last simulations, CS 23, an open book policy with suppliers, unexpectedly failed when previously it succeeded. In cases like this, the model can give the modeller more of an insight into possible reasons. Different variables may be manipulated, such as commitment, or different character combinations explored, both of which may lead to valuable answers for management.

The evolutionary framework with more basic research has the potential to become a practical tool (a software package) for management to guide and explore decision-making in various scenarios and would aim to provide three primary sources of aid for manufacturers. The first would provide a blueprint with which manufacturers could use to guide the transition to more competitive practices. The second form of aid would be the potential simulations of organisations that may not have yet been attempted and be a potential source of competitive advantage. The third way in which the approach may aid manufacturers is that their particular organisation may be simulated and new characteristics (e.g. new technologies and practices) may be added. This could help identify problem areas in terms of inhibition or facilitation and be a useful tool for reducing risk and uncertainty in decision-making processes.

9.4. Further Research Recommendations

This research has led to three main areas to recommend for further research: a) modelling the sustainable evolution of manufacturing; b) modelling evolutionary processes involved in industrial ecosystems; and c) modelling the potentially different views of key people in management, with the underlying notion of bounded rationality, that have influence of the major decisions.

9.4.1. Evolving Sustainable Manufacturing Organisations

The original research aim of this thesis was to develop cladograms describing the evolution of sustainable manufacturing (highlighted in chapters 1, 4 and 5). In chapter 6, it was also highlighted that this could also be built upon and include evolutionary systems modelling so that in addition to an exploration of the past, with the cladograms, there would also be opportunities to explore the future.

In terms of sustainable development, manufacturing industry is in a unique position – often cited as the cause of many environmental and social problems, but also the main mechanism for change through economic growth (WCED, 1987). One of the main barriers now to sustainable industrial development is not the lack of strategies, models and tools (see for example van Berkel et al, 1997), but how to implement them, and more importantly how to introduce them into existing practices whilst ideally improving competitiveness. Management uncertainty among other barriers is undermining the progress toward sustainable industrial development.

Further research is needed to guide transformations and explore the evolutionary differences between sustainable and non-sustainable organisations, and identify new structures offering industry novel solutions for sustainability (see the sections concerning further research in chapters 5 and 6 for more details of this research direction). Three main areas of further research are identified as:

1. The interaction between existing and sustainable technologies and practices
2. The extent and relative importance of the fundamental processes involved in the evolution of sustainable manufacturing systems
3. The decision-making processes related to sustainable change initiatives.

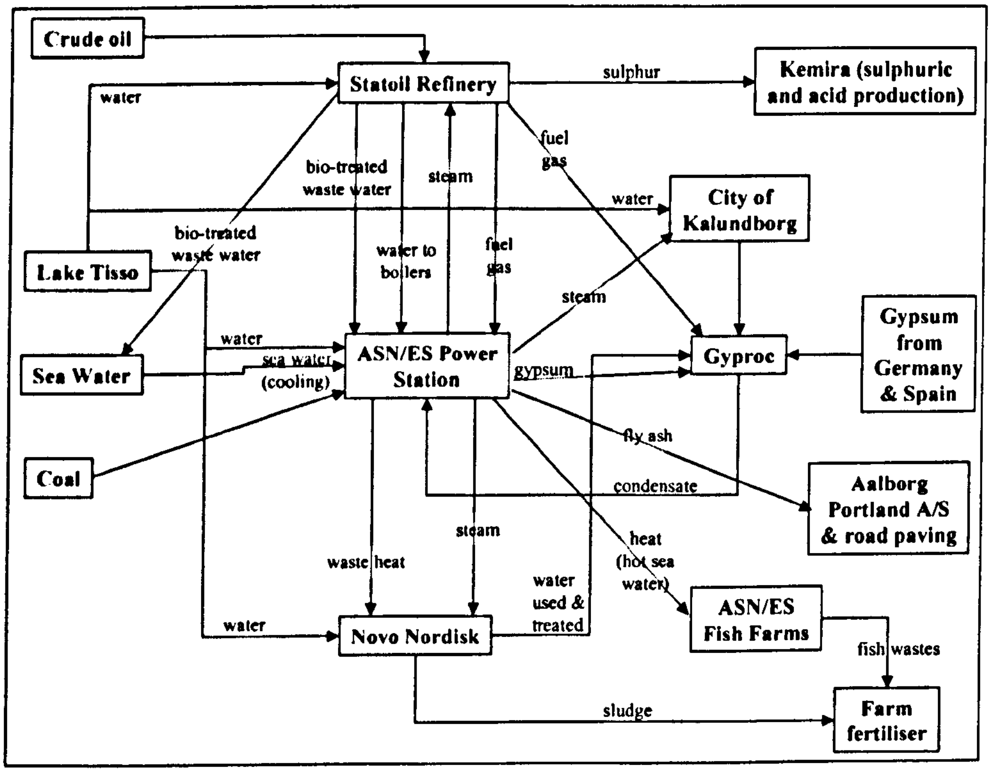
9.4.2. Modelling Industrial Ecosystems and the Problem of Evolution

The second area of potential research concerns the models that have been developed in the field of industrial ecology, particularly the apparent disconnect (e.g. O'Rourke et al, 1996) between definitions and modelling. The arguments of modelling discussed in chapter 6 are reinforced when looking at models of industrial ecosystems. Before looking at models of IE however, it is ironic that in many of the definitions, forwarded by researchers and practitioners, evolution is a central theme, but is at worst ignored and at best confused with the optimisation of energy and material flows. An example, one frequently cited definition, which interestingly emphasises both optimisation and evolution, is as follows (Allenby, 1994: 47):

> 'Industrial ecology may be defined as the means by which a state of sustainable development is approached and maintained. It consists of a systems view of human economic activity and its interrelationship with fundamental biological, chemical, and physical systems with the goal of establishing and maintaining the human species at levels that can be sustained indefinitely – given continued economic, cultural and technological evolution.'

This disconnect between definitions and models as well as the confusion between evolution and optimisation can be demonstrated with the now classic example of an industrial ecosystem. Figure 9.2 depicts the industrial symbiosis situated in Kalundborg, Denmark. Admittedly, this model tells you something of the present whilst also giving you a glimpse of the past.

Figure 9.2. The industrial symbiosis at Kalundborg

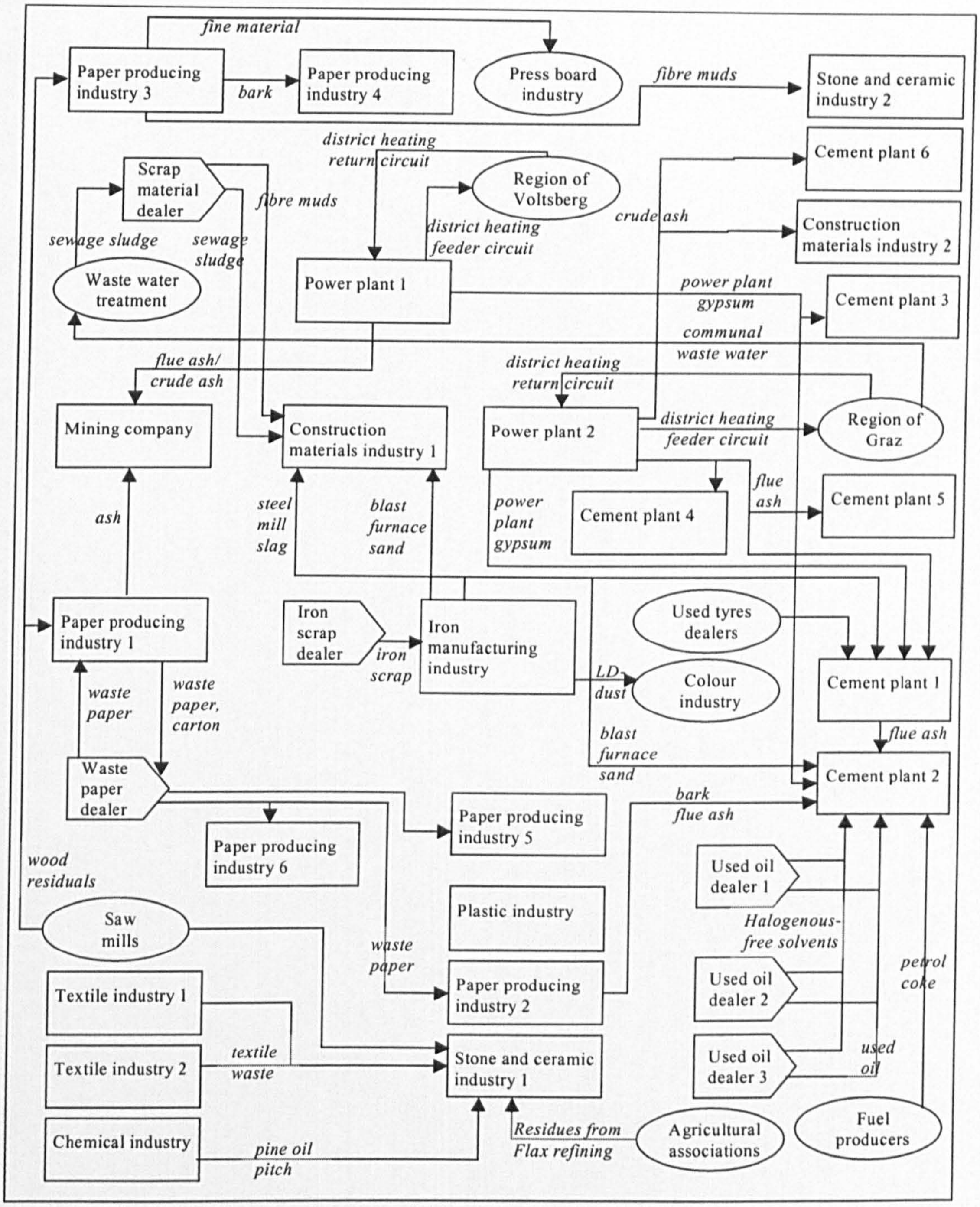


There are two main points here both concerning modelling. The first is that the actual Kalundborg system was guided from the beginning by a similar model (or thinking behind the model) to that described in figure 9.2. That is, researchers and practitioners with a mechanical and reductionist approach developed a model beforehand that guided the practical development of the system. The model prioritised optimisation of materials and energy flow, as recommended by IE, through symbiotic relationships between the companies. However, as a consequence of optimisation, variety, micro-diversity, redundancy and 'slack' within the system was sacrificed. This, as can be seen from the discussion of evolutionary systems and the Law of Excess Diversity in chapter 6, has significantly diminished the capacity to change, to respond to external events and to experiment, and thus to evolve. This is why the system is now regarded to be highly rigid and vulnerable, and is ultimately a consequence of mechanical models (Allen, 1994).

In practical terms, if, for example, Gyproc or Statoil Refinery went bankrupt, were taken over, or just decided not to partake in the system any longer, the model would have to be redrawn. Furthermore, the whole structure of the actual system would be seriously threatened and would probably collapse. Structural change is not limited to only that example – new innovations, new external pressures, such as legislation and public pressure, mergers and takeovers, new energy sources and new materials are all common instigators of change. If the model had a mathematical basis, the equations governing change would have to be calibrated or re-thought out. The model *itself* has no capacity to change qualitatively.

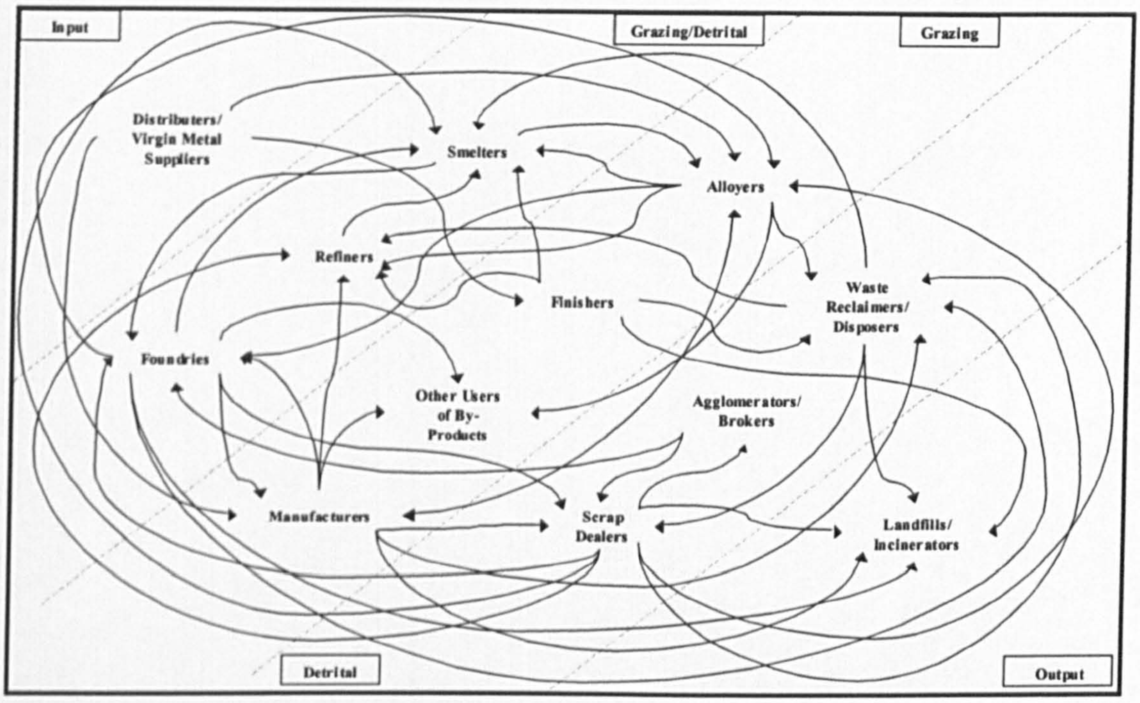
When taking the example of the Styrian system and the metals-manufacturing systems, both discussed in more detail in chapter 2, the problem is somewhat different. The first difference is that these systems happened spontaneously without any model for guidance and were later 'discovered' *then* modelled (see figure 9.3 for the Styrian system). Without the guiding model, the system is arguably far more fluid, there is far more diversity, and thus redundancy, giving the system far more flexibility and adaptive capability. The danger now is that there *is* a model available, giving the modeller and IE practitioners far more incentive to begin optimising.

Figure 9.3. Recycling structures in Styria (from Schwarz & Steininger, 1997)



When looking at the Styrian system, the model still suffers the same problems to the Kalundborg system in that although being a good description of the present with glimpses of the past, there is no indication of what may happen in the future. When relating the metals-manufacturing system of Massachusetts (see figure 9.4), similar in composition to that in Sheffield's early metals-manufacturing system, there is no hint of future decline as happened in Sheffield (see chapter 4). Clearly, models are needed that take account of real-life qualitative change that may drive the system in many possible future directions, including decline.

Figure 9.4. Metals manufacturing system (adapted from Sagar & Frosch, 1997)



The evolutionary framework, with its simulation capabilities, in contrast to typical models, may be applied and the real processes underlying evolution may be explored. For example, simulations of future scenarios of industrial ecosystems and the consequences of particular decisions may be explored with respect to normal systemic and environmental events such as the introduction of innovative (and sustainable) technology, policy and legislative changes, new actors emerging, mergers and takeovers. The most applicable models that may be employed are those reviewed in chapter 6 concerning urban and economic systems.

9.4.3. Character-State Interaction and Bounded Rationality

The research reported in this thesis has begun to answer some of the questions concerned with uncertainty and unpredictability in management decision-making. Building on this work, further research is needed to investigate the different attitudes and opinions of different people that have significant input into the decision-making process involved in change and organisational transformations in one organisation. In the previous research the opinions of manufacturing managers, operations manager, CEOs and company directors were analysed in an aggregated manner, i.e. the data were averaged out. As such, significant information was lost. Further research would need to compare and contrast the views of different people and, through evolutionary modelling and simulation, examine the consequences of decision-making from people that inevitably have different opinions and base their decisions on different information, values and beliefs. It is obvious that in the research reported in this thesis that the respondents had different views of how technologies and practices interacted with one another. These diverse views have the potential to radically affect the evolution of a company particularly in times of change (e.g. introducing a new technology, practice or policy).

The aim would be to explore the views of different people in an organisation (e.g. manufacturing managers, operations manager and CEOs) and the consequences of these diverse views in the evolution of the organisation. In economics the notion of 'bounded rationality' could be used as the framework for the research. Bounded rationality refers to the incomplete knowledge that people have and use (and the misuse of information) when decision-making (Allen, 1998b). The data that would be required will have to be collected from both interviews and questionnaires from respondents that have a significant impact in the decision-making processes involved in change. Through simulation comparisons and contrasts can be made between the different people, and give an insight into the effects of the bounded rationality of decisions and their consequences as well as the overall evolutionary trajectories that can be taken.

9.3. Modelling Manufacturing Evolution: Conclusions

The results of the simulations presented in chapter 8 have provided several matters for discussion. Firstly the significance of the results were discussed and included the different techniques employed to evolve organisations, different perspectives the model provides in that individual character-states may be tracked throughout the evolutionary history, an in-depth investigation into the innovation process involved in evolution, and the problems and issues involved in organisational change initiatives and transformations. The discussion then explored several potential reasons of why certain character-states failed during the simulations. Reasons include design and questionnaire flaws, sampling procedures, flaws in the original research by McCarthy et al (1997), and issues relating to weighting, chronology, missing character-states, and synergetic bundles of characteristics. The main application of this new evolutionary framework, in terms of a practical tool for helping with decision-making, was then highlighted. As the model explored possible evolutionary trajectories, the impacts of new technologies and practices can be identified as well as conflicting character-states.

Three main areas of further research were then recommended and discussed in detail. The first area concerned issues highlighted in the first section of this thesis and relate to sustainable technologies and practices. The model could be used as a tool to help explore the impacts and consequences of new technologies and practices helping a potentially smoother transition to sustainable manufacturing. Similarly, the next research recommendation relates to the models of industrial ecology (IE) and problem of modelling evolution. The new evolutionary framework has the potential to revolutionise the techniques modellers have used to date in this new field of inquiry. Although similar techniques have been employed in for example geography and environmental science for decades, IE has yet to utilise such tools.

The third area of potential further research expands on the work in this thesis and includes the notion of bounded rationality in the decision-making process. As the research reported in this thesis took the aggregated opinions of manufacturers as the measures of interactivity, information was inevitably lost. The aim of the recommended research would aim to model and then compare and contrast potentially conflicting ideas of how character-states interact and therefore explore potentially different evolutionary trajectories based on these differences.

CHAPTER 10 – THESIS CONCLUSIONS

10. Introduction

The aim of this thesis was to apply new understanding and concepts from the science of complex systems in an industrial context. Several research aims were attempted. The first part of the thesis (chapters 2 to 4) was concerned with the theoretical modelling of both sustainable complex systems in general and sustainable industrial systems, the latter with a focus on the metals-manufacturing system in the region of South Yorkshire. Chapters five through to nine concentrated on modelling the cladistic evolution of automotive assembly plants and was a combination of manufacturing cladistics and evolutionary systems modelling.

10.1. Aims and Objectives of the Thesis

The first main aim was to identify issues concerning sustainable industrial development and regeneration whilst also determining whether new ideas emerging out of complex systems thinking would shed light on the problem. The specific research aims were:

- To develop a theoretical generic model of sustainable complex systems
- To develop a theoretical model that creates a framework within which sustainable industrial networks can be represented and understood
- To extend the debate in industrial ecology beyond the metaphor and the typical focus of industrial ecology models
- To generate, through modelling, guidelines with which regional/national policy- and decision-makers can follow
- To provide a theoretical framework for the justification of applying biological concepts and classification techniques to manufacturing organisations

The second main aim, which evolved and changed as the research evolved, was to model the cladistic evolution of manufacturing. The final research aims were:

- To build on and interpret two complimentary but currently unrelated areas of research – manufacturing cladistics and evolutionary systems modelling

- To explore through simulation the interaction of an organisation's different technologies and practices, and investigate the effects of introducing new technologies and practices
- To determine the usefulness of this new evolutionary framework in terms of both evolving industrial structures and future trajectories that manufacturing can take.

10.2. Thesis Conclusions

10.2.1. Sustainability and Industrial Ecology

One important concept explored in the thesis was sustainability. The most accepted definition of sustainable development was proposed in *Our Common Future* and is referred to as '*development which meets the needs of the present without compromising the ability of future generations to meet their own needs*'. Of particular importance, in the translation from definition to strategy, is the recognition that although problems are global in scale, action and intervention can only be initiated locally. The industrial process is in a unique position as it is often seen as both the cause of most problems, while also the main mechanism for change i.e. sustainable economic growth. Strategies, models and tools specific to industrial sustainability have centred mainly on principles from industrial ecology.

From the review of industrial ecology a number of problems and issues were raised and further recommendations for research highlighted. This literature review (chapter 2) provided the foundation for the development of the two models presented in chapters 3 and 4. The IE literature regarding definitions, models, case studies, and strategy and tool development (as well as problems with all of the above), has developed rapidly. There are now many IE models including industrial metabolism models, extended metabolism models, and the more popular IE models such as the Type I-III industrial ecosystems. Other ecological phenomena have also been explored such as energy transitions, diversity, locality, and gradual change. However, no research has as yet attempted to develop a full overview.

Having reviewed the case studies of Kalundborg, Styria and Massechusetts several important observations and criticisms were drawn out. The first observation is that these systems developed naturally through normal economics and with no external pressures. As such there may be countless systems that exist but not yet identified. One criticism is that some of these systems, such as Kalundborg with its hard-pipe connections, have a high degree of rigidity. This may stifle innovation and reduce adaptability and resilience in the future. Other systems, however, such as the Styrian and metals-manufacturing system are, in contrast, characterised by diffuse and diverse connections which should prevent rigidity.

10.2.2. Model of Sustainable Complex Systems

This conceptual model consisted of an exploration into the physical fundamentals of sustainable complex systems and aimed to extend the debate in industrial ecology by proposing a more intimate relationship between natural and anthropogenic systems. The motivation behind this was the case study (reviewed in chapter 2) of the closed-looping behaviour of the metals-manufacturing system in Massachusetts. Of particular interest, was that the system closed its materials cycle without any major intervention from politicians, industrialists or environmentalists (i.e. without a global blueprint). The model therefore proposed arguments towards the notion that the sustainability of industrial systems is a natural phenomenon.

The model based its arguments on the first principles of physics. Firstly, the roots of complex systems thinking were discussed, Newtonian Mechanics and classical thermodynamics, in addition to contemporary schools of complexity thought. Secondly, specific concepts such as gradient degradation, the ordering processes of natural selection (competition and co-operation) and autopoiesis were examined. Examples from a number of systems were utilised ranging from simple hydrodynamic systems to highly complicated ecological systems.

The model demonstrated *how* evolutionary complex systems may arise - when the system is open and when a gradient is applied; *why* they arise - they function to degrade the gradient; *how* the maximum effectiveness of function is reached - natural selection; and, *how* the system sustains its function - autopoiesis. One of the objectives of these arguments was to enable the building of models of industrial development that consider industry and natural ecology as homology rather than analogy. In addition, hypotheses such as energy flows, diversification, life histories and climax may now be tested.

10.2.3. The N-ET Model

The N-ET (Non-Equilibrium Thermodynamic) model of the industrial development of metals manufacturing was essentially a synthesis of disparate theories, drawing primarily from complex systems thinking, systems ecology, industrial ecology, and networking theory. This model, building on the former model (chapter 3), examined the industrial process from a theoretical framework derived from first principles: the non-equilibrium thermodynamic paradigm of systemic development. Characteristic metabolic behaviour observed in systems, open to fluxes of energy and matter, appear to reconcile physics, biology, ecology, and the industrial developmental process. Open systems, in attempting to degrade the impinging energy gradients, utilise the available matter and metabolise it. In doing so, the self-organisation of ordered process structures occurs, gradients are degraded, and entropy produced and exported increasingly faster.

The specific case study for the N-ET model was South Yorkshire with its rich industrial history of metals manufacturing. The main conclusions drawn from the review were many and particularly significant when developing models of the sustainable industrial development of a region. The review focused on the development, the clustering phenomenon, and industrial decline of several sectors of which the core material was steel. Initial conditions, trajectories of development, the major events that helped shape the evolutionary processes, and the present composition and structure of the industry were concluded to be the most significant issues behind both the region's success and decline.

The N-ET model, building on models of ecosystem development, assumed that systems with a physical metabolism exhibit patterns, therefore eliciting predictions, not only in structure, function and organisation but also in evolution and development. The hypotheses were organised under the following headings:

1. The closed-loop hypothesis
2. The energy hypothesis
3. The diversification hypothesis
4. The selection hypothesis
5. The punctuated systemic control hypothesis.

Methodology consisted of data collection from existing literature sources and historical records. Although South Yorkshire was the specific case study, certain data sources were either incomplete or absent. Therefore data representative of the South Yorkshire situation, metals manufacturing areas, or from national and international databanks from which general trends could be identified, were also used. Preliminary support for the model was found in these existing databases.

The proposed model of industrial development was developed to meet several goals. Firstly, it aimed to extend and support both the concept of IE and Schneider and Kay's non-equilibrium thermodynamic paradigm of life. One of the main differences between the model proposed here and IE is that it proposes a homology rather than analogy. Another contrast is that where IE focuses primarily on closing the material loops of industrial networks, this model also introduced other systemic phenomena that are particularly useful when considering industrial development and regeneration. For example, general hypotheses drawn from the model assumed that patterns similar to that in nature might be observed not only in closed-looping behaviour, but also in energy usage, diversification, selection pressures and systemic stability. Guidelines were also specified with which regional/national policy- and decision-makers can follow.

Another aim of this model was to develop a better understanding of the issues involved in sustainable industrial regeneration. As well as enhancing insight into the issues involved in the sustainable development and regeneration of regions and industrial communities, the novelty of this approach also introduces scope for increasing understanding of the transitions needed for existing companies to remain competitive in mature metabolic systems – the second main aim of the thesis.

10.2.4. Manufacturing Cladistics

In classification science it was found that there are two main biological principles – phenetics and phylogenetics. From these, three main classification disciplines have emerged – the phenetic, evolutionary and cladistic approaches. These schools can be thought of as lying on one dimension – the evolutionary scale. Phenetics is non-evolutionary and lies at one extreme. Cladistics in based purely on evolutionary principles and lies at the other extreme. Evolutionary classifications are a synthesis of the two and lie in the middle of the scale.

After reviewing the three schools to assess their ability to construct natural and objective classifications (rather than artificial and subjective), it was concluded that only cladistics could fully satisfy these criteria. By using evolution as an external reference point (evolutionary history cannot be changed), classifications will be unique and unambiguous. Cladistics is now the most accepted approach in biology and as such is the most appropriate starting point for manufacturing classifications. Manufacturing cladistics was first developed not only as a classification scheme, but also as an aid for organisational change initiatives. There are now several good working examples including cladistic classifications of the hand-tool industry, management styles and the automotive industry.

The original research aim was to develop cladograms describing the evolution of sustainable manufacturing, which would complement the models in chapters 3 and 4. However, it was concluded that manufacturing cladistics, as it is a post-hoc analysis, only represents the past. To remain competitive an exploration of possible futures is required. Therefore, further research to be pursued by the thesis concerned a synthesis of manufacturing cladistics with evolutionary systems modelling. This would allow simulations to be made of the evolution of manufacturing entities so that potential organisations could be identified, decisions explored and that a guide could be developed that would help manufacturers during change initiatives and organisational transformations.

10.2.5. Evolutionary Systems Modelling

The problem of modelling evolutionary processes was highlighted and the typical assumptions that are made when trying to model complex systems. The more assumptions made the more mechanical and simplified the model. To accurately reflect evolutionary processes models need to refute the notion of equilibrium, have interactions between system components that reflect non-average behaviour (i.e. that the processes are not averaged out), and have system components that are non-average (i.e. the notion of micro-diversity).

This kind of model has now been used to simulate the behaviour of natural ecosystems, environmental systems, urban centres, and economic systems. In all of the research projects reviewed several consistent conclusions emerged. The first conclusion is that as evolution is more accurately modelled the less the model is capable of predicting. The model however, does allow for explorations of many possible future states that could occur. In addition, models of this kind give the modeller a much deeper insight into the system under study particularly the non-physical aspects such as strategy, learning and *how* to change to adapt to the system and environment.

It was concluded that by combining manufacturing cladistics and evolutionary systems modelling techniques, the problems associated with the former (i.e. it is only a post-hoc analysis) can be solved and potential future manufacturing organisations can be investigated. In addition, consequences of decision-making and implications of change initiatives may be explored as well as the identification of potential inhibiting and/or facilitating technologies and practices.

Ideally, research would be conducted firstly into developing a cladogram of the evolution of sustainable manufacturing and then gather the data of the interactions between the characteristics identified so that simulations could be performed of the evolutionary processes involved in sustainable manufacturing. However, as this would have constituted two large research projects it was decided that a compromise had to be taken. Therefore it was decided that a pilot study was needed to assess the feasibility of the synthesis. The case study chosen was the manufacturing cladistics research on the automotive industry reviewed in chapter 5.

10.2.6. Methodology Behind the Modelling of Manufacturing Evolution

There were two main aspects to the methodology: The data collection process and the simulation model. As this was an altogether new investigative approach, the methodology was of an exploratory nature rather than an established one. The aim of the research was not to apply the findings but to determine if the approach had a potential viability for application, in short, to see whether the data collected actually worked with the model and if similar findings were found to that in the study of the automotive industry.

Data was collected from a questionnaire survey. The objective of the questionnaire was to gauge the opinions of manufacturers of how characteristics of the automotive industry interacted on one another. The questionnaire was then sent to 1,565 to manufacturing organisations. Seventy-three were returned equating to just less than an expected 5% return rate (4.66%). The evolutionary systems model that was utilised had numerous variables that could be manipulated and calibrated. The first was the running time of the evolutionary model. This may be adjusted to accommodate reaching the final solution. The second variable is the number of characteristics launched in the model. This can be controlled so that specific organisational forms may be explored. The third variable is the starting value of the characteristic. Characteristics may have a value between 0-28 units. The value may be thought of as the success of the characteristic or the importance of the characteristic to the organisation. Most of the runs reported launch the characteristics with a starting value of 5.

10.2.7. Results of Modelling Manufacturing Evolution

Chapter 8 presented the results of the simulations of the cladistic evolution of automotive assembly plants. There were five main sets of results. The first explored the evolution of organisational form according to previous research on manufacturing cladistics. This entailed evolving organisations in a consecutive procedure where the values of the characteristics were taken into the next evolutionary run. The second set of results tracked individual character-states through the full evolution of the organisational forms.

An alternative procedure to the full evolutionary run formed the third set of results. This procedure entailed launching each organisation with the values of all character-states equal. Comparisons and contrasts were made to both the original manufacturing cladistics work and the full evolutionary run. The fourth set of results investigated the innovation process. This procedure entailed launching organisations with just the first character-state and then randomly launching other character-states. The procedure allowed for 200 introductions (and re-introductions) over a lengthy time period. The final set of results investigated change initiatives and organisational transformations. Three main areas concerning quality, workforce and supplier policies were explored.

10.2.8. Discussion of the Modelling of Manufacturing Evolution

A discussion of the significance of the investigation's results constituted chapter 9. Firstly it was concluded that this modelling technique provided original and novel insights and observations when applied to the evolution of manufacturing practices and technologies. The first observation was that 11 of the 53 character-states failed during the simulations limiting the description of the evolution to just 42 characteristics. In addition, one of the character-states that failed was the only distinguishing feature between two organisations and as such reduced the total number of organisations to just 15. This led to a re-think of the evolutionary history and the construction of an amended cladogram. The tracking of the performance of individual character-states gave an alternative perspective of the evolution and provided unique insights into the diverse relationships between the character-states and the organisations as well as additional insights into failure and commitment.

The third set of results, which launched each character-state with equal values, offered an alternative procedure to the full evolutionary run. With different initial conditions different evolutionary trajectories were explored and different stable solutions were reached. Although the results had many similarities to the full evolutionary run, there were important differences and offered an alternative view of the evolutionary history. An amended cladogram was constructed that reflected these differences.

The investigation into the innovation process further explored character-state failures, issues of commitment, and the rise of domineering character-states and bundles of character-states. The re-introduction of character-states, which reflects a reduction of confidence or commitment, was particularly interesting. Several characteristics appeared to be successfully integrated into the organisation but when the commitment was challenged they rapidly disappeared from the simulation. The stable solutions of all five random innovation processes mirrored, with only a few differences, the stable solution of the Agile Producer (from both the full and individual evolutionary runs). It may be concluded therefore that the Agile Producer is a very strong structural attractor within the simulation model.

With the exploration of organisational transformations important insights were provided into commitment, the decision-making process, risk and unpredictability in management, and the interaction of individual and synergetic bundles of characteristics. Change initiatives and organisational transformations were the main reasons for the development of manufacturing cladistics in the first instance. The model demonstrated its ability to explore certain decisions, the consequences of those decisions and the potential new organisational structures that emerged. The results of some simulations were logical in that older characteristics were replaced by newer and more efficient practices and technologies. Other results were surprising and were thought to be due to the subtle interactions in the model and/or influential synergetic bundles that had developed. The model also demonstrated its capacity over longer time horizons and to explore consequences with delayed effects.

Of particular significance was the failure of important character-states during the simulations and may have been due to several other reasons. The first and most obvious reason could be the fault of the questionnaire design, i.e. misinterpretation. In addition, there may also be a question of weighting the characteristics. There were also questions such as timing of introduction, i.e., some characteristics would be introduced earlier than others and some may also be precursors. Another possibility may be due to certain characteristics having ‘bad press’ in the media, which may influence opinions on certain interactions. Similarly, there is also a question of psychological barriers, in terms of perceptions and biased opinions, to certain characteristics. Finally, the issue of the population form where the data was collected was highlighted, in that the sample was from a population of general manufacturers rather than the automotive industry. Nonetheless, the accuracy or validity of the original manufacturing cladistics work is called into question.

The main conclusion from this investigation was that research in this new field and information and tools that it would generate would be valuable for manufacturing organisations. It will facilitate a reflection of the possible innovations, new ideas, disrupting technologies, and threats and opportunities that they face. The tools could arguably provide practical assistance in seeing options and in assessing their benefits and costs. The new evolutionary framework may identify threats to their longer-term survival, and in addition lead to choices of innovations and changes that have greater efficiency and cheaper running costs in the future. The ideas emerging from complex and evolutionary systems thinking have caused considerable excitement, but not as yet a great many practical results. The research reported here is a promising step in this direction.

10.3. Originality

The thesis contained five main novel outcomes:

- A model of the physical fundamental of sustainable complex systems detailing how and why systems emerge and the underlying processes involved in optimisation and sustainability
- A model of industrial development that utilises thinking in non-equilibrium thermodynamics and extends both the metaphor debate in IE and the use of other phenomenological attributes characteristic of natural ecosystems
- A combination of manufacturing cladistics and evolutionary systems modelling
- A unique data collection methodology to determine the interaction of common manufacturing technologies and practices
- The simulation of the evolution of manufacturing technologies and practices.

10.4. Further research

Although several research recommendations were made throughout most of the chapters, three main future projects were argued to be the most fruitful. The first is the simulation of the evolution of sustainable manufacturing organisations. Further research is needed to guide transformations and explore the evolutionary differences between sustainable and non-sustainable organisations, and identify new structures offering industry novel solutions for sustainability. Applying the evolutionary framework may provide a useful decision-making aid for manufacturers in their bid to become more sustainable. Through the identification of sustainability characteristics and their synthesis with more traditional characteristics, it would be possible to explore problems of technology transfer, potential consequences in all areas of organisation, and new sustainable structural solutions.

The second area of research relates to the models developed in chapters 3 and 4. The evolutionary framework, with its simulation capabilities, in contrast to typical models, may be applied and the real processes underlying evolution may be explored. For example, simulations of future scenarios of industrial ecosystems and the consequences of particular decisions may be explored with respect to normal systemic and environmental events such as the introduction of innovative (and sustainable) technology, policy and legislative changes, new actors emerging, mergers and takeovers.

The third area of research that was recommended is a more in-depth investigation into the decision-making processes and the effects of people's different perceptions, values and their use of (limited) information. The notion of bounded rationality from economics would provide the framework for the investigation. Further research would need to compare and contrast the views of different people and, through evolutionary modelling and simulation, examine the consequences of decision-making from people that inevitably have different opinions and base their decisions on different information, values and beliefs.

REFERENCES

Aldenderfer, M. S. and Blashfield, R. K. (1984). Cluster Analysis. Sage Publications Ltd.

Allen, P. M. (1976). "Evolution, population dynamics, and stability." Proceedings of the National Academy of Science (USA) **73**: 665-668.

Allen, P. M. (1978). "Dynamique des centres urbains." Sciences et Techniques **50**: 15-19.

Allen, P. M. (1982). The genesis of structure in social systems: The paradigm of self-organisation. Theory and Explanation in Archaeology. Renfrew, C., Ed. New York: Academic Press: 347-374.

Allen, P. M. (1984). Self-organisation and evolution in urban systems. Cities and Regions as Non-Linear Decision Systems. Crosby, R., Ed. AAAS Selected Symposia 77, Westview Press, Boulder Colorado: 29-62.

Allen, P. M. (1992). "Evolutionary theory, policy making and planning." Journal of Scientific and Industrial Research **51**: 644-657.

Allen, P. M. (1994). Evolution, sustainability and industrial metabolism. Industrial Metabolism. Ayres, R. and Simonis, U., Eds. Tokyo: United Nations University Press.

Allen, P. M. (1997). "Cities and regions as evolutionary complex systems." Geographical Systems **4**: 103-130.

Allen, P. M. (1998a). Evolving complexity in social science. Systems: New Paradigms for the Human Sciences. Altmann, G. and Koch, W. A., Eds. Berlin and New York: Walter de Gruyter.

Allen, P. M. (1998b). Modelling complex economic evolution. Selbstorganisation. Scheiter, F. and Silverberg, G., Eds. Berlin: Duncker and Humblot.

Allen, P. M. (2001a). "A complex systems approach to learning, adaptive networks." International Journal of Innovation Management **5**(2): 149-180.

Allen, P. M. (2001b). The dynamics of knowledge and ignorance: Learning the new systems science. Integrative Approaches to Natural and Social Dynamics. Matthies, M., Malchow, H. and Kriz, J., Eds. Berlin: Springer Verlag.

Allen, P. M. (2001c). Knowledge, ignorance and the evolution of complex systems. Frontiers of Evolutionary Economics: Competition, Self-Organisation and Innovation Policy. Foster, J. and Metcalfe, S., Eds. Cheltenham, UK: Edward Elgar.

Allen, P. M. (2001d). "What is the science of Complexity? - Knowledge of the limits to knowledge." Emergence 3(1): 24-42.

Allen, P. M. and Ebeling, W. (1983). "Evolution and the stochastic description of simple ecosystems." Biosystems **16**: 113-126.

Allen, P. M., Engelen, G. and Sanglier, M. (1984). Self-organising dynamic models of human systems. From Microscopic to Macroscopic Order. Frehland, E., Ed. Berlin: Springer: 150-171.

Allen, P. M. and McGlade, J. M. (1986). "Dynamics of discovery and exploitation: The Scotian Shelf Fisheries." Canadian Journal of Fisheries and Aquatic Sciences **43**(6): 1187-1200.

Allen, P. M. and McGlade, J. M. (1987). "Evolutionary drive: The effect of microscopic diversity, error making and noise." Foundations of Physics **17**(7): 723-728.

Allen, P. M. and Sanglier, M. (1978). "Dynamic models of urban growth." Journal of Social and Biological Structures **1**: 265-280.

Allen, P. M. and Sanglier, M. (1979a). "A dynamic model of growth in a central place system." Geographical Analysis **11**(3): 256-272.

Allen, P. M. and Sanglier, M. (1979b). "A dynamic model of urban growth-II." Journal of Social and Biological Structures **2**: 269-278.

Allen, P. M. and Sanglier, M. (1981). "Urban evolution, self-organization and decision making." Environment and Planning A **13**: 167-183.

Allen, P. M., Sanglier, M., Engelen, G. and Boon, F. (1985). "Towards a new synthesis in the modelling of evolving complex systems." Environment and Planning B **12**: 65-84.

Allenby, B. R. (1994). Integrating environment and technology: design for environment. The Greening of Industrial Ecosystems. Allenby, B. and Richards, D., Eds. Washington DC: National Academy Press: 137-148.

Arief, A. (1998). A Sustainability Assessment of Squatter Redevelopment on Jakarta. Unpublished MPhil Thesis, Murdoch University.

Ashby, R. (1960). Design for a Brain. Wiley: New York.

Atkins, P. W. (1984). The Second Law. New York: W. H. Freeman and Company.

Axelrod, R. and Hamilton, W. D. (1981). "The evolution of cooperation." Science **211**: 1390-1396.

Ayres, R. U. (1994). Industrial metabolism: theory and policy. The Greening of Industrial Ecosystems. Allenby, B. and Richards, D., Eds. Washington DC: National Academy Press: 23-37.

Azzone, G. and Bertele, U. (1994). "Exploiting green strategies for competitive advantage." Long Range Planning **27**(6): 69-81.

Baerlocher, F. (1990). "The Gaia hypothesis: A fruitful fallacy." Experientia **46**: 232-238.

Bailey, K. D. (1998). "Social ecology and living systems theory." Systems Research and Behavioural Science **15**: 421-428.

Bailey, R., Bras, B. and Allen, J. K. (1999). "Using robust concept exploration and systems dynamics models in the design of complex industrial ecosystems." Engineering Optimization **32**(1): 33-58.

Barbier, E. (1987). "The concept of sustainable economic development." Environmental Conservation **14**(2): 101-110.

Barbier, E. B. and Markandya, A. (1990). "The conditions for achieving environmentally sustainable development." European Economic Review **34**: 659-669.

Barlow, C. and Volk, T. (1990). "Open systems living in closed biosphere: A new paradox for the Gaia debate." BioSystems **23**: 371-384.

Barlow, C. and Volk, T. (1992). "Gaia and evolutionary biology." BioScience **42**(9): 687-693.

Beckerman, W. (1994). "Sustainable development: Is it a useful concept?" Environmental Values **3**(3): 191-209.

Benci, V. and Galleni, L. (1998). "Stability and instability in evolution." Journal of Theoretical Biology **194**: 541-549.

Berke, P. R. and Conroy, M. M. (2000). "Are we planning for sustainable development: An evaluation of 30 comprehensive plans." Journal of the American Planning Association **66**(1): 21-33.

Bjorklund, A., Dalemo, M. and Sonesson, U. (1999). "Evaluating a municipal waste management plan using ORWARE." Journal of Cleaner Production **7**: 271-280.

Bonabeau, E. (1998). "Social insect colonies as complex adaptive systems." Ecosystems **1**: 437-443.

Boons, F. A. A. and Baas, L. W. (1997). "Types of industrial ecology: The problem of coordination." Journal of Cleaner Production **5**(1-2): 79-86.

Bramanti, A. and Senn, L. (1991). Innovation, firms and milieu: a dynamic and cyclic approach. Innovation Networks. Camagni, R., Ed. London: Bellhaven Press: 89-104.

Brearley, H. (1995). Steel-Makers and Knotted String. London: Institute of Materials.

Brown, S., Margulis, L., Ibarra, S. and Siqueiros, D. (1985). "Desiccation resistance and contamination as mechanisms of Gaia." BioSystems **17**: 337-360.

Bruff, G. and Wood, A. (1995). "Sustainable development in English metropolitan district authorities: An investigation using unitary development plans." Sustainable Development **3**(1): 9-19.

Brundtland, G. H. (1989). "How to secure our common future." Scientific American **261**(3): 134.

Buenstorf, G. (2000). "Self-organization and sustainability: Energetics of evolution and implications for ecological economics." Ecological Economics **33**: 119-134.

Burns, T. P. (1994). "One the fittedness of organisms and the ascendency of ecosystems: Toward a hierarchical model of network development." Journal of Theoretical Biology **170**: 115-127.

Camagni, R. (1991). Introduction: From the local 'milieu' to innovation through cooperation networks. Innovation Networks. Camagni, R., Ed. London: Bellhaven Press: 1-9.

Cantlon, J. E. and Koenig, H. E. (1999). "Sustainable ecological economics." Ecological Economics **31**: 107-121.

Carnot, S. (1890). Reflections on the motive power of heat and on machines fitted to develop that power. London: Macmillan.

Carper, W. B. and Snizek, W. E. (1980). "The nature and types of organisational taxonomies: An overview." Academy of Management Review **5**(1): 66-75.

Cattell, R. B. (1952). Factor Analysis. Harper New York.

Chakrabarti, C. G., Ghosh, S. and Bhadra, S. (1995). "Non-equilibrium thermodynamics of Lotka-Volterra ecosystems: Stability and evolution." Journal of Biological Physics **21**: 273-284.

Chapin, F. S., Torn, M. S. and Tateno, M. (1996). "Principles of ecosystem sustainability." The American Naturalist **148**(6): 1016-1037.

Chapman, A. W. (1955). The Story of a Modern University: A History of the University of Sheffield. Oxford.

Chiesa, V., Manzini, R. and Noci, G. (1999). "Towards a sustainable view of the competitive system." Long Range Planning **32**(5): 519-530.

Christensen, N. L., Bartuska, A. M., Brown, J. H., Carpenter, S., D'Antonio, C., Francis, R., Franklin, J. F., MacMahon, J. A., Noss, R. F., Parsons, D. J., Peterson, C. H., Turner, M. G. and Woodmansee, R. G. (1999). "The report of the Ecological Society of America committee on the scientific basis for ecosystem management." Ecological Applications **6**(3): 665-691.

Christensen, V. (1995). "Ecosystem maturity - towards quantification." Ecological Modelling **77**: 3-32.

Clark, W. C. (1989). "Managing planet earth." Scientific American **261**(3): 19-26.

Commoner, B. (1997). "The relation between industrial and ecological systems." Journal of Cleaner Production **5**(1-2): 125-129.

Connell, J. H. (1979). Tropical rain forests and coral reefs as open non-equilibrium systems. Population Dynamics. Anderson, R. M., Turner, B. D. and Taylor, L. R., Eds. Oxford: Blackwell: 95-111.

Connell, J. H. and Slatyer, R. O. (1977). "Mechanisms of succession in natural communities and their role in community stability and organisation." American Naturalist **111**: 1119-1144.

Cooke, P. and Morgan, K. (1993). "The network paradigm: New departures in corporate and regional development." Environment and Planning D: Society and Space **11**: 543-564.

Cormack, R. M. (1971). "A review of classification." Proceedings of the Royal Statistical Society **3**: 321-367.

Costanza, R. (1993). "Developing ecological research that is relevant for achieving sustainability." Ecological Applications 3(4): 579-581.

Costanza, R., Daly, H. E. and Bartholomew, J. A. (1991). Goals, agenda, and policy recommendations for ecological economics. Ecological Economics: The Science and Management of Sustainability. Costanza, R., Ed. New York: Columbia University Press: 1-20.

Costanza, R. and Perrings, C. (1990). "A flexible assurance bonding system for improved environmental management." Ecological Economics **2**: 57-75.

Costanza, R., Wainger, L., Folke, C. and Maler, K. G. (1993). "Modelling complex ecological-economic systems." Bioscience **43**(8): 545-555.

Cote, R. P. and Cohen-Rosenthal, E. (1998). "Designing eco-industrial parks: A synthesis of some experiences." Journal of Cleaner Production **6**: 181-188.

Craik, J. C. A. (1989). "The Gaia hypothesis - fact or fancy?" Journal of the Marine Biological Association of the United Kingdom **69**: 759-768.

Crossley, D., Cass, N., Flavell, N. and Turner, C., Eds. (1989). Water Power on the Sheffield Rivers. Sheffield.

Crosson, P. R. and Rosenberg, N. J. (1989). "Strategies for agriculture." Scientific American **261**(3): 78-85.

Dale, V. H., Brown, S., Haeuber, R. A., Hobbs, N. T., Huntly, N., Naiman, R. J., Riebsame, W. E., Turner, M. G. and Valone, T. J. (1999). "Ecological principles and guidelines for managing the use of land." Ecological Applications (in press).

Daly, H. (1990). "Towards some operational principles of sustainable development." Ecological Economics **2**: 1-6.

Daly, H. E. (1994). Operationalizing sustainable development by investing in natural capital. Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Jansson, A., Hammer, M., Folke, C. and Costanza, R., Eds. Washington DC: Island Press: 22-37.

Darwin, C. (1859). The Origin of the Species by Means of Natural Selection. London: John Murray.

Dasgutpa, P. S. (1995). "Population, poverty and the local environment." Scientific American **272**(2): 40-45.

Dawkins, R. (1986). The Blind Watchmaker. Longman Scientific & Technical.

Dawkins, R. (1989). The Selfish Gene. 2nd Ed Oxford University Press.

Demetrius, L. (1977). "Adaptedness and fitness." American Naturalist **111**: 1163-1168.

Desrochers, P. (2002). "Regional development and inter-industry recycling linkages: some historical perspectives." Entrepreneurship and Regional Development **14**(1): 49-65.

DETR. Department of Environment Transport and the Regions. (1998a). Sustainable Development: Opportunities for Change - Consultation Paper on a Revised UK Strategy.

DETR. Department of Environment Transport and the Regions. (1998b). Sustainable Development: Opportunities for Change - Sustainable Business.

DETR. Department of Environment Transport and the Regions. (1999a). A Better Quality of Life: A Strategy for Sustainable Development for the United Kingdom.

DETR. Department of Environment Transport and the Regions. (1999b). Quality of Life Counts: Indicators for a Strategy for Sustainable Development for the United Kingdom - A Baseline Assessment.

DETR. Department of Environment Transport and the Regions. (1999c). A Way with Waste: Draft Waste Strategy for England and Wales.

Diamond, J. (1991). The Rise and Fall of the Third Chimpanzee: How Our Animal Heritage Affects the Way We Live. Cox & Wyman Ltd Reading.

Dincer, I. (2000). "Renewable energy and sustainable development: A crucial review." Renewable and Sustainable Energy Reviews **4**: 157-175.

Diver, G., Newman, P. W. G. and Kenworthy, J. (1996). An Evaluation of Better Cities: Environmental Component. Canberra: Department of Environment, Sport and Territories.

Donald, C. M. (1958). "The interaction of competition for light and for nutrients." Australian Journal of Agricultural Research **9**: 421-432.

Downing, K. and Zvirinsky, P. (2000). "The simulated evolution of biochemical guilds: Reconciling Gaia theory and natural selection." Artificial Life **5**: 291-318.

Dugdale, J. S. (1996). Entropy and its Physical Meaning. Taylor & Francis.

Ehrenfeld, J. R. (1997). "Industrial ecology: A framework for product and process design." Journal of Cleaner Production **5**(1-2): 87-95.

Ehrlich, P. R. and Daily, G. C. (1993). "Science and the management of natural resources." Ecological Applications **3**(4): 558-560.

Eigen, M. (1971). "Self-organization of matter and the evolution of biological macromolecules." Naturwissenchaften **58**: 465-523.

Eigen, M. and Schuster, P. (1977). "The hypercycle: A principle of natural self-organization in three parts : Part A: Emergence of the hypercycle." Naturwissenchaften **64**: 541-565.

Eigen, M. and Schuster, P. (1978a). "The hypercycle: A principle of natural self-organization in three parts : Part B: The abstract hypercycle." Naturwissenchaften 65: 7-41.

Eigen, M. and Schuster, P. (1978b). "The hypercycle: A principle of natural self-organization in three parts : Part C: The realistic hypercycle." Naturwissenchaften 65: 347-36.

Eigen, M. and Schuster, P. (1979). The Hypercycle. Berlin: Springer.

Ekvall, T. (1999). "Key methodological issues for life cycle inventory analysis of paper recycling." Journal of Cleaner Production 7: 281-294.

Elmer-Dewitt, P. (1989a). "Nuclear power plots a comeback." Time, January 2. pp. 28.

Elmer-Dewitt, P. (1989b). "Preparing for the worst." Time, January 2. pp. 44-45.

Erkman, S. (1997). "Industrial ecology: A historical perspective." Journal of Cleaner Production 5(1-2): 1-10.

Everitt, B. (1986). Cluster Analysis. Gower Publishing Aldershot.

Farzin, Y. H. (1984). "The effect of the discount rate on depletion of exhaustible resources." Journal of Political Economy 92: 841-851.

Fitch, W. M. (1984). Cladistics and Other Methods: Problems, Pitfalls and Potentials. Columbia University Press New York.

Foray, D. (1990). "The secrets of industry are in the air." Research Policy 20(5): 393-405.

Freeman, C. (1991). "Networks of innovators: A synthesis of research issues." Research Policy 20(5): 499-514.

Frosch, R. A., Clark, W. C., Crawford, J., Sagar, A., Tschang, F. T. and Webber, A. (1997). "The industrial ecology of metals: A reconnaissance." Philosophical Transactions of the Royal Society of London Part A 355: 1335-1347.

Frosch, R. A. and Gallopoulos, N. E. (1989). "Strategies for manufacturing." Scientific American 261(3): 94-102.

Frosch, R. A. and Uenohara, M. (1994). Chairmen's Overview. Indsutrial Ecology U.S. Japan Persepctives. Richardson, D. J. and Fullerton, A. B., Eds. Washington, DC: National Academy of Engineering.

Fuentes, E. R. (1993). "Scientific research and sustainable development." Ecological Applications 3(4): 576-577.

Gibbons, J. H., Blair, P. D. and Gwin, H. L. (1989). "Strategies for energy use." Scientific American 261(3): 86-93.

Gibson, C. C., Ostrom, E. and Ahn, T. K. (2000). "The concept of scale and the human dimensions of global change: A survey." Ecological Economics 32: 217-239.

Gillies, J. (2000). A Complex Systems Model of the Adaptability of Industrial Networks. Unpublished Ph D Thesis, University of Cranfield.

Gladwin, T. N., Kennelly, J. J. and Krause, T. S. (1995a). "Shifting paradigms for sustainable development: Implications for management theory and research." Academy of Management Review **20**(4): 874-907.

Gladwin, T. N., Krause, T. and Kennelly, J. J. (1995b). "Beyond eco-efficiency: Towards socially sustainable business." Sustainable Development **3**(1): 35-43.

Glansdorff, P. and Prigogine, I. (1971). Thermodynamics of Structure, Stability and Fluctuations. New York: Wiley Interscience.

Goh, P. (2000). The Implementation of Total Quality Management in Small to Medium Sized Enterprises. Unpublished Ph D Thesis, University of Sheffield.

Good, I. J. (1965). Categorisation of Classification. Mathematics and Computer Science in Medicine and Biology London: H. M. S. O.

Gordon, R. (1991). Innovation, industrial networks and high-technology regions. Innovation Networks. Camagni, R., Ed. London: Bellhaven Press: 174-195.

Gorham, E. (1991). "Biogeochemistry: Its origins and development." Biogeochemistry **13**: 199-239.

Gould, S. J. (1982). "Darwinism and the expansion of evolutionary theory." Science **216**: 380-387.

Gould, S. J. (1989). Wonderful Life. Hutchinson Radius.

Gould, S. J. and Eldridge, N. (1977). "Punctuated equilibria: The tempo and mode of evolution reconsidered." Paleobiology **3**: 115-151.

Graedel, T. E. (1996). "On the concept of industrial ecology." Annual Review of Energy and the Environment **21**: 69-98.

Graedel, T. E. and Crutzen, P. J. (1989). "The changing atmosphere." Scientific American **261**(3): 28-36.

Grime, J. P. (1974). "Vegetation classification by reference to strategies." Nature **250**: 26-31.

Grime, J. P. (1977). "Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory." American Naturalist **111**: 1169-1194.

Grime, J. P. (1979a). Competition and the struggle for existence. Population Dynamics. Anderson, R. M., Turner, B. D. and Taylor, L. R., Eds. Oxford: Blackwell: 123-139.

Grime, J. P. (1979b). Plant Strategies and Vegetation Processes. Chichester: Wiley & Sons.

Grime, J. P. (1981). An ecological approach to management. Amenity Grassland: An Ecological Perspective. Rorison, I. H. and Hunt, R., Eds. London: Wiley: 13-55.

Grime, J. P. (1984). "The ecology of species, families and communities of the contemporary British flora." New Phytologist **98**: 15-33.

Grime, J. P. (1986). Manipulation of plant species and communities. Ecology and Design in Landscape. Bradshaw, A. D., Thorpe, E. and Goode, D. A., Eds. Oxford: Blackwell: 175-194.

Grime, J. P. (1998). The C-S-R model of primary plant strategies - origins, implications and tests. Plant Evolutionary Biology. Gottlieb, L. D. and Kain, S. K., Eds. Chapman & Hall London: Ch. 14.

Grubb, P. J. (1977). "The maintenance of species-richness in plant communities: The importance of the regeneration niche." Biological Reviews **52**: 107-145.

Grübler, A. (1994). Industrialisation as a historical phenomenon. The Greening of Industrial Ecosystems. Allenby, B. and Richards, D., Eds. Washington DC: National Academy Press: 43-68.

Haas, J., Hall, R. and Johnson, N. (1966). Toward an empirically derived taxonomy of organisations. Studies on Behaviour in Organisations. Bovers, R., Ed. Athens GA: University of Georgia Press.

Haken, H. and Mikhailov, A., Eds. (1993). Interdisciplinary Approaches to Nonlinear Complex Systems. New York: Springer.

Hardin, G. (1968). "The tragedy of the commons." Science **162**: 1243-1248.

Hartvigsen, G., Kinzig, A. and Peterson, G. (1998). "Use and analysis of complex adaptive systems in ecosystem science: Overview of special selection." Ecosystems **1**: 427-430.

Hatsopoulos, G. and Keenan, J. (1965). Principles of General Thermodynamics. New York: John Wiley.

Hawken, P. (1993). The Ecology of Commerce: A Declaration of Sustainability. London: Phoenix.

Hennig, W. (1950). Grundzuge einer theorie der phylogenetischen systematik. Deutscher Zentraverlag: Berlin.

Hern, W. M. (1990). "Why are there so many of us? Description and diagnosis of a planetary ecopathological process." Population and Environment **12**: 9-39.

Hey, D. (1991). The Fiery Blades of Hallamshire: Sheffield and its Neighbourhood, 1660-1740. Leicester.

Holland, J. (1824). The Picture of Sheffield. Sheffield.

Holland, J. (1995). Hidden Order: How Adaptation Builds Complexity. Reading (MA): Addison-Wesley.

Huggett, R. J. (1999). "Ecosphere, biosphere, or Gaia ? What to call the global ecosystem." Global Ecology and Biogeography **8**: 425-431.

Hunter, J. (1869). Hallamshire: The History and Topography of the Parish of Sheffield in the County of York. Sheffield.

Huston, M. (1979). "A general hypothesis of species diversity." American Naturalist **113**: 81-101.

Janssen, M. (1998). "Use of complex adaptive systems for modelling global change." Ecosystems **1**: 457-463.

Jantsch, E. (1980). The Self-Organizing Universe: Scientific and Human Implications of the Emerging Paradigm of Evolution. Pergamon Press Oxford.

Kamann, D. J. and Strijker, D. (1991). The network approach: concepts and applications. Innovation Networks. Camagni, R., Ed. London: Bellhaven Press: 145-173.

Kauffman, S. (1995). At Home in the Universe: The Search for the Laws of Self-Organization and Complexity. Oxford University Press.

Kearns, F. R. (1997). "Human population and consumption: What are the ecological limits?" Bulletin of the Ecological Society of America **78**(2): 161-163.

Keeble, D. (1997). "Small firms, innovation and regional development in Britain in the 1990s." Regional Studies **31**(3): 281-293.

Ketsin, J. (1968). A Course in Thermodynamics. New York: Hemisphere Press.

Kirchner, J. W. (1989). "The Gaia hypothesis: Can it be tested." Reviews of geophysics **27**(2).

Klein, D. R. (1968). "The introduction, increase, and crash of reindeer on St. Matthew Island." Journal of Wildlife Management **32**: 350-367.

Kondepudi, D. and Prigogine, I. (1998). Modern Thermodynamics: From Heat Engines to Dissipative Structures. John Wiley & Sons Chichester.

Korhonen, J. (2001). "Four ecosystem principles for an industrial ecosystem." Journal of Cleaner Production **9**: 253-259.

Krumbein, W. E. and Schellnhuber, H. J. (1992). "Geophysiology of mineral deposits - a model for a biological driving force of global changes through Earth history." Terra Nova **4**: 351-362.

Langone, J. (1989). "Waste: A stinking mess." Time, January 2. pp. 30-32.

Lawton, J. H. (1995). "Ecological experiments with model systems." Science **269**: 328-331.

Lazarsfield, P. L. and Henry, N. W. (1968). Latent Structure Analysis. Houghton Miffin Co. Boston.

Lemonick, M. D. (1989a). "Deadly danger in a spray can." Time, January 2. pp. 29.

Lemonick, M. D. (1989b). "Global warming: Feeling the heat." Time, January 2. pp. 24-27.

Lenton, T. M. (1998). "Gaia and natural selection." Nature **394**: 439-447.

Leps, J. M., Osbornova-Kosinova, J. and Rejmanek, K. (1982). "Community stability, complexity and species life-history strategies." Vegetatio **50**: 53-63.

Leseure, M. (1998). Manufacturing Cladistics: Using Phylogenetic Classifications to Understand and Manage the Complexification of Manufacturing Systems. Unpublished Ph D Thesis, University of Sheffield.

Leseure, M. (2000). "Manufacturing strategies in the hand tool industry." International Journal of Operations and Production Management **20**(12): 1475-1487.

Levin, S. A. (1998). "Ecosystems and the biosphere as complex adaptive systems." Ecosystems **1**: 431-436.

Levine, L. (1993). "Gaia: Goddess and idea." BioSystems **31**: 85-92.

Lewin, R. (1999). Complexity: Life at the Edge of Chaos. 2nd Ed The University of Chicago Press.

Lloyd-Jones, R., Lewis, M. and Gore, V. (1994). "Sheffield History Proves Small is Beautiful." Guardian, 7th February.

Loreau, M. (1998). "Ecosystem development explained by competition within and between material cycles." Proceedings of the Royal Society of London **165**: 33-38.

Lovelock, J. E. (1979). Gaia: A New Look at Life on Earth. Oxford University Press.

Lovelock, J. E. (1985). "Are we destabilising world climate? The lessons of geophysiology." The Ecologist **15**(1-2): 52-55.

Lovelock, J. E. (1988). The Ages of Gaia: A Biography of Our Living Earth. Oxford University Press.

Lovelock, J. E. (1989a). "Gaia." Journal of the Marine Biological Association of the United Kingdom **69**: 746-758.

Lovelock, J. E. (1989b). "Geophysiology, the science of Gaia." Reviews of geophysics **27**(2): 215-222.

Lovelock, J. E. (1990). "Hands up for the Gaia hypothesis." Nature **344**: 100-102.

Lovelock, J. E. (1997). "A geophysiologist's thoughts on the natural sulphur cycle." Philosophical Transactions of the Royal Society of London - Series B - Biological Sciences **352**: 143-147.

Lowe, A. J. (1999). Applying QFD in Manufacturing SMEs. Unpublished Ph D Thesis, University of Sheffield.

Lowe, E. A. (1997). "Creating by-product resource exchanges: Strategies for eco-industrial parks." Journal of Cleaner Production **5**(1-2): 57-65.

Lubchenco, J., Olson, A. M., Brubaker, L. B., Carpenter, S. R., Holland, M. M., Hubbell, S. P., Levin, J. A., MacMahon, J. A., Matson, P. A., Melillo, J. M., Mooney, H. A., Peterson, C. H., Pulliam, H. R., Real, L. E., Regal, P. J. and Risser, P. G. (1991). "The sustainable biosphere initiative: An ecological research agenda." Ecology **72**: 371-412.

Ludwig, D. (1993). "Environmental sustainability: Magic, science, and religion in natural resource management." Ecological Applications **3**(4): 555-558.

Ludwig, D., Hilbron, R. and Walters, C. (1993). "Uncertainty, resource exploitation, and conservation: Lessons from history." Ecological Applications **3**(4): 547-549.

MacNeill, J. (1989). "Strategies for sustainable economic development." Scientific American **261**(3): 105-113.

Maddison, W. P. and Maddison, D. R. (1992). MacClade version 3: Analysis of Phylogeny and Character Evolution. Massachusetts, USA: Sinauer Associates Inc.

Mageau, M. T., Costanza, R. and Ulanowicz, R. E. (1998). "Quantifying the trends expected in developing ecosystems." Ecological Modelling **112**: 1-22.

Mangel, M., Hofman, R. J., Norse, E. A. and Twiss, J. R. (1993). "Sustainability and ecological research." Ecological Applications **3**(4): 573-575.

Margulis, L. and Lovelock, J. E. (1974). "Biological modulation of the Earth's atmosphere." Icarus **21**: 471-489.

Maynard-Smith, J. (1982). Evolution and the Theory of Games. Cambridge: University Press.

McCarthy, I. P. (1995a). The Development of a Manufacturing Classification using Concepts from Organisational Systematics and Biological Taxonomy. Unpublished Ph D Thesis, University of Sheffield.

McCarthy, I. P. (1995b). "Manufacturing classification: Lessons from organizational systematics and biological taxonomy." Integrated Manufacturing Systems **6**(6): 37-48.

McCarthy, I. P., Leseure, M., Ridgway, K. and Fieller, N. (1997). "Building a manufacturing cladogram." International Journal of Technology Management **13**(3): 269-286.

McCarthy, I. P., Leseure, M., Ridgway, K. and Fieller, N. (2000). "Organisational diversity, evolution and cladistic classifications." The International Journal of Management Science **28**: 77-95.

McCarthy, I. P. and Ridgway, K. (2000). "Cladistics: A taxonomy for manufacturing organizations." Integrated Manufacturing Systems **11**: 116-29.

McKelvey, B. (1982). Organisational Systematics: Taxonomy Evolution, Classification. University of California Press Berkeley.

Meadows, D. H., Meadows, D. L. and Randers, J. (1992). Beyond the Limits: Confronting Global Collapse - Envisioning a Sustainable Future. Post Mills, VT: Chelsea Green.

Meyer, J. L. and Helfman, G. S. (1993). "The ecological basis of sustainability." Ecological Applications **3**(4): 569-571.

Moffat, A. S. (1996). "Biodiversity, productivity and stability." Science **271**: 1497.

Mooney, H. A. and Sala, O. E. (1993). "Science and sustainable use." Ecological Applications **3**(4): 564-566.

Muezzinoglu, A. (1998). "Air pollutant emission potentials of cotton textile manufacturing industry." Journal of Cleaner Production **6**: 339-347.

Myers, N. (1987). "Population, environment, and conflict." Environmental Conservation **14**(2): 15-22.

Newman, E. I. (1973). "Competition and diversity in herbaceous vegetation." Nature **244**: 310.

Newman, P. W. G. (1999). "Sustainability and cities: Extending the metabolism model." Landscape and Urban Planning **44**: 219-226.

Newton, I. (1687). Principia (Philosphiæ naturalis principia mathematica). Londini: Jussu Societatis Regiæ ac Typis Josephi Streater. Prostat apud plures Bibliopolas.

Nicolis, G. and Prigogine, I. (1971). "Fluctuations in nonequilibrium systems." Proceedings of the National Academy of Science (USA) **68**(9): 2102-2107.

Nicolis, G. and Prigogine, I. (1977). Self-Organisation in Non-Equilibrium Systems. New York: Wiley Interscience.

Nicolis, G. and Prigogine, I. (1989). Exploring Complexity. New York: Freeman.

O'Rourke, D., Connelly, L. and Koshland, C. P. (1996). "Industrial ecology: A critical review." International Journal of Environment and pollution **6**(2-3): 89-112.

Odum, E. P. (1969). "The strategy of ecosystem development." Science **164**: 262-270.

Odum, E. P. (1971). Fundamentals of Ecology. 3rd Ed London: Saunders.

Odum, E. P. (1972). Ecology. Holt London.

Odum, E. P. (1997a). "Commentary: Source reduction, input management and dual capitalism." Journal of Cleaner Production **5**(1-2): 123.

Odum, E. P. (1997b). Ecology: A Bridge Between Science and Society. Sunderland Massachusetts: Sinauer.

Odum, E. P. and Biever, L. J. (1984). "Resource quality, mutualism, and energy partitioning in food chains." The American Naturalist **124**: 360-376.

Park and Seaton (1996). "Integrative research and sustainable agriculture." Agricultural Systems **50**: 81-100.

Patten, B. C. and Odum, E. P. (1981). "The cybernetic nature of ecosystems." The American Naturalist **118**: 886-895.

PCSD. U.S. President's Council on Sustainable Development (1994). A Vision for a Sustainable U.S. and Principles of Sustainable Development.

Pezzey, J. (1992). "Sustainability: An interdisciplinary guide." Environmental Values **1**: 321-362.

Pickett, S. T. A. (1980). "Non-equilibrium co-existence of plants." Bulletin of the Torrey Botanical Club **107**: 238-248.

Pitelka, L. F. and Pitelka, F. A. (1993). "Environmental decision making: Multidimensional dilemmas." Ecological Applications 3(4): 566-568.

Pizzocaro, S. (1998). "Steps to industrial ecology: Reflections on theoretical aspects." International Journal of Sustainable Development and World Ecology 5: 229-237.

Policansky, D. (1993). "Uncertainty, knowledge, and resource management." Ecological Applications 3(4): 583-584.

Pollard, S. (1959). A History of Labour in Sheffield: The Sheffield Outrages. Liverpool.

Polunin, N. (1987). "Energy-use and the biosphere." Environmental Conservation 14(2): 4-5.

Porter, M. E. and van der Linde, C. (1995). "Green and competitive: Ending the stalemate." Harvard Business review: 120-134.

Potter, V. R. (1987). "Aldo Leopold's land ethic revisited: Two kinds of bioethics." Perspectives in Biology and Medicine 30(2): 157-169.

Powell, W. (1990). Neither market nor hierarchy: Network forms of organisation. Research in Organisational Behaviour, Volume 12. Straw, B. and Cummings, L., Eds. JAI Press Greenwich CT: 74-96.

PRB (1999). 1999 World Population Data Sheet. www.prb.org/pubs/wpds99/wpds99_world.htm

Prigogine, I. (1973). "Irreversibility as a symmetry-breaking process." Nature 246: 67-71.

Prigogine, I. and Stengers, I. (1987). Order out of Chaos. New York: Bantam Books.

Putman, R. J. and Wratten, S. D. (1984). Principles of Ecology. London: Croom Helm.

Ratti, R. (1991). Small and medium-sized enterprises, local synergies and spatial cycles of innovation. Innovation Networks. Camagni, R., Ed. London: Bellhaven Press: 71-88.

Rees, W. E. and Wackernagel, M. (1994). Ecological footprints and appropriated carrying capacity: Measuring the natural capital requirements of the human economy. Investing in Natural Capital: The Ecological Economics Approach to Sustainability. Jansson, A., Hammer, M., Folke, C. and Costanza, R., Eds. Washington DC: Island Press: 363-390.

Richards, D. J., Allenby, B. R. and Frosch, R. A. (1994). The greening of industrial ecosystems - overview and perspectives. The Greening of Industrial Ecosystems. Allenby, B. and Richards, D., Eds. Washington DC: National Academy Press: 1-19.

Ridley, M. (1982). Evolution and Classification, the Reformation of Cladism. Longman U.S.

Ridley, M. (1993). Evolution. Blackwell Scientific Publications.

Ripper, W. (1910). Engineering Industry of the District. British Association Handbook & Guide to Sheffield. Sheffield.

Roberts, P. (1995). Environmentally Sustainable Business: A Local and Regional Perspective. Paul Chapman Publishing Ltd London.

Ross, H. (1974). Biological Systematics. Addison-Wesley Reading MA.

Ruckelshaus, W. D. (1989). "Towards a sustainable world." Scientific American **261**(3): 114-120.

Sagan, D. and Margulis, L. (1983). "The Gaian perspective of ecology." The Ecologist **13**(5): 160-167.

Sagar, A. D. and Frosch, R. A. (1997). "A perspective on industrial ecology and its application to a metals-industry ecosystem." Journal of Cleaner Production **5**(1-2): 39-45.

Salwasser, H. (1993). "Sustainability needs more than a better science." Ecological Applications 3(4): 587-589.

Sancton, T. A. (1989a). "Hands across the sea: Rich and poor, north and south, nations must get it together or face common disaster." Time, January 2. pp. 36-40.

Sancton, T. A. (1989b). "Planet of the year." Time, January 2. pp. 14-17.

Saxenian, A. (1991). "The origins and dynamics of production networks in Silicon Valley." Research Policy **20**(5): 423-437.

Schneider, E. D. and Kay, J. J. (1994). "Complexity and thermodynamics: Towards a new ecology." Futures **26**(6): 626-647.

Schneider, S. H. (1989). "The changing climate." Scientific American **261**(3): 38-47.

Schrödinger, E. (1944). What is Life? Cambridge University Press Cambridge.

Schwartzkopf, S. H. (1992). "Design of a controlled ecological life support system: Regenerative technologies are necessary for implementation in a lunar base CELSS." Bioscience **42**(7): 526-535.

Schwarz, E. J. and Steininger, K. W. (1997). "Implementing nature's lesson: The industrial recycling network enhancing regional development." Journal of Cleaner Production **5**(1-2): 47-56.

SFP. Sheffield First Partnership. (1999a). Developing Sheffield's Economy for the 21st Century.

SFP. Sheffield First Partnership. (1999b). Review of Assisted Areas of Great Britain. Sheffield: A Positive Response - The Case for Development Area Status for Sheffield and South Yorkshire.

Shannon, C. E. and Weaver, W. (1949). The Mathematical Theory of Communication. University of Illinois Press Urbana IL.

Slobodkin, L. B. (1993). "Scientific goals require literal empirical assumptions." Ecological Applications 3(4): 571-573.

Socolow, R. H. (1993). "Achieving sustainable development that is mindful of human imperfection." Ecological Applications 3(4): 581-583.

Southwood, T. R. E. (1977). "Habitat, the templet for ecological strategies?" Journal of Animal Ecology **46**: 337-365.

Spreng, D. T. (1984). On the entropy of economic systems. From Microscopic to Macroscopic Order. Frehland, E., Ed. Berlin: Springer: 207-217.

Suarez, F., Cusumano, M. and Fine, C. (1995). "An empirical study of flexibility in manufacturing." Sloan Management Review **Fall**: 25-32.

Swenson, R. (1992). "Autocatakinetics, yes - autopoiesis, no: Steps towards a unified theory of evolutionary ordering." International Journal of General Systems **21**: 207-228.

Szekely, J. (1996). "Steelmaking and industrial ecology - is steel a green material." ISIJ International **36**: 121-132.

Szekely, J. and Trapaga, G. (1995). "Industrial ecology - the need to rethink the materials cycle: Some problems, solutions, and opportunities in the materials field." Journal of Materials Research **10**(9): 2178-2196.

Tainter, J. A. (1988). The Collapse of Complex Societies. Cambridge University Press.

Templet, P. H. (1996). "The energy transition in international economic systems: An empirical analysis of change during development." International Journal of Sustainable Development and World Ecology **3**: 13-30.

Templet, P. H. (1999). "Energy, diversity and development in economic systems: An empirical analysis." Ecological Economics **30**: 223-233.

Tickell, C. (1993). "Gaia: Goddess or thermostat." BioSystems **31**: 93-98.

Tietenberg, T. (1994). Environmental economics and policy. HarperCollins College Publishers.

Todd, A. D. (1998). The Engineering Design Process: A Numerical Taxonomy. Unpublished Ph D Thesis, University of Sheffield.

Toufexis, A. (1989). "Overpopulation: Too many mouths." Time, January 2. pp. 33-35.

Toussaint, O. and Schneider, E. D. (1998). "The thermodynamics and evolution of complexity in biological systems." Comparative Biochemistry and Physiology Part A **120**: 3-9.

Tsinopoulos, C. and McCarthy, I. P. (1997). "Achieving agility using cladistics: An evolutionary analysis." Journal of Materials Processing Technology **107**: 338-346.

Tweedale, G. (1987). Sheffield Steel and America: A Century of Commercial and Technological Interdependence 1830-1930. Cambridge University Press.

Tweedale, G. (1995). Steel City: Entrepreneurship, Strategy and Technology in Sheffield, 1743-1993. Clarendon Press Oxford.

Ulanowicz, R. E. (1980). "A hypothesis on the development of natural communities." Journal of Theoretical Biology **85**: 223-245.

Ulanowicz, R. E. and Abarca-Arenas, L. G. (1997). "An informational synthesis of ecosystem structure and function." Ecological Modelling **95**: 1-10.

UNCED. United Nations Commission on Environment and Development (1992). Agenda 21. UN, New York.

UNFPA. United Nations Population Fund (1991). The State of World Population 1991. UNFPA, New York.

van Berkel, R., Willems, E. and Lafleur, M. (1997). "Development of an industrial ecology toolbox for the introduction of industrial ecology in enterprises - I." Journal of Cleaner Production 5(1-2): 11-25.

Varela, F., Maturana, H. R. and Uribe, R. (1974). "Autopoiesis: The organization of living systems, its characterization and a model." BioSystems 5: 187-196.

Verheul, H. (1999). "How social networks influence the dissemination of cleaner technologies to SMEs." Journal of Cleaner Production 7: 213-219.

Verschoor, A. H. and Reijnders, L. (1999). "The use of life cycle methods by seven major companies." Journal of Cleaner Production 7: 375-382.

Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H. and Matson, P. A. (1986). "Human appropriation of the products of photosynthesis." Bioscience 36(6): 368-373.

Waldrop, M. M. (1992). Complexity: The Emerging Science at the Edge of Order and Chaos. Penguin Books.

Wallner, H. P. (1999). "Towards sustainable development of industry: networking, complexity and eco-clusters." Journal of Cleaner Production 7: 49-58.

Wallner, H. P., Narodoslawsky, M. and Moser, F. (1996). "Islands of sustainability: A bottom-up approach towards sustainable development." Environment and Planning A 28: 1763-1778.

Washida, T. (1995). "Ecosystem configurations consequent on the maximum respiration hypothesis." Ecological Modelling 78: 173-193.

Watson, J. D. and Crick, F. H. C. (1953). "Molecular structure of nucleic acids – A structure for deoxyribonucleic acid." Nature 171: 737.

WCED. Oxford University Press, Oxford, England (1987). Our Common Future.

WCU. World Conservation Union, United Nations Environment Programme, and World Wide Fund for Nature (1991). Caring for the Earth: A Strategy for Sustainable Living.

Welford, R. (1994). Cases in Environmental Management and Business Strategy. London: Pitman.

Welford, R. (1995). Environmental Strategy and Sustainable Development: The Corporate Challenge for the 21st Century. London: Routledge.

Welford, R. (1997). Hijacking Environmentalism: Corporate Responses to Sustainable Development. London: Earthscan.

Welford, R. and Gouldson, A. (1993). Environmental Management and Business Strategy. Glasgow: Pitman.

Wicken, J. S. (1978). "Information transformations in molecular evolution." Journal of Theoretical Biology **72**: 191-204.

Wicken, J. S. (1979). "The generation of complexity in evolution, a thermodynamic and information, theoretical discussion." Journal of Theoretical Biology **77**: 349-365.

Wicken, J. S. (1980). "Thermodynamic theory of evolution." Journal of Theoretical Biology **87**: 9-23.

Wilbur, H. M., Tinkle, D. W. and Collins, J. P. (1974). "Environmental certainty, trophic level, and resource availability in life history evolution." American Naturalist **108**: 805-817.

Wiley, E. O., Siegel-Causey, D., Brooks, D. R. and Funk, V. A. (1991). The complete cladist – a primer of phylogenetic procedures. Special Publicaitons no. 19. The University of Kansas Museum of Natural History.

Wilkinson, D. M. (1999a). "Gaia and natural selection." Tree **14**(7): 256-257.

Wilkinson, D. M. (1999b). "Is Gaia really conventional ecology." Oikos **84**(3): 533-536.

Womack, J. P., Jones, D. T. and Roos, D. (1990). The Machine that Changed the World. New York: MacMillan Publishing.

Wu, J. and Loucks, O. L. (1995). "From balance of nature to hierarchical patch dynamics: A paradigm shift in ecology." The Quarterly Review of Biology **70**(4): 439-466.

Zedler, J. B. (1993). "Lessons on preventing over-exploitation?" Ecological Applications **3**(4): 577-578.

Zeleny, M. and Hufford, K. D. (1992). "The application of autopoiesis in systems analysis: Are autopoietic systems also social systems." International Journal of General Systems **21**: 145-160.

APPENDIX 1 - CONCEPTUAL DEFINITIONS OF SUSTAINABLE DEVELOPMENT AND SUSTAINABILITY.

> [Sustainable development is] development that meets the needs of the present without compromising the ability of future generations to meet their own needs.

(WCED, 1987: 8)

Since the Brundtland report (WCED, 1987), many, more detailed definitions have emerged in the academic literature, more or less in line with this initial definition. Although in all definitions there is considerable emphasis on the environment, most explicitly recognise that it is human development (achieving at least the same or better living conditions and the widening of people's choices) respective of ecological, social and economic systems; or human development that culminates in the enhancement of economic, social and ecological capital.

> Improving the quality of human life while living within the carrying capacity of supporting ecosystems.

(WCU, 1991: 10)

> Sustainable development: At its heart is the simple idea of ensuring a better life for everyone, now and for generations to come. Its means meeting four objectives at the same time, in the UK and the world as a whole: social progress which recognises the needs of everyone; effective protection of the environment; prudent use of natural resources; and, maintenance of high and stable levels of economic growth and employment.

(DETR, 1999a - Chapter 1, Section 1-2)

Our vision is of a life-sustaining earth. We are committed to the achievement of a dignified, peaceful, and equitable existence. We believe a sustainable United States will have an economy that equitably provides opportunities for satisfying livelihoods and a safe, healthy, high quality of life for current and future generations. Our nation will protect its environment, its natural resource base, and the functions and viability of natural systems on which all life depends.

(PCSD, 1994: 1)

To maximise simultaneously the biological system goals (genetic diversity, resilience, biological productivity), economic system goals (satisfaction of basic needs, enhancement of equity, increasing useful goods and services), and social system goals (cultural diversity, institutional sustainability, social justice, participation).

(Barbier, 1987: 103)

Sustainability is a relationship between dynamic human economic systems and larger dynamic, but normally slower-changing ecological systems, in which a) human life can continue indefinitely, b) human individuals can flourish, and c) human cultures can develop; but in which effects of human activities remain within bounds, so as not to destroy the diversity, complexity, and function of the ecological life support system.

(Costanza, Daly & Bartholomew, 1991: 8)

A sustainable society is one that can persist over generations, one that is far-seeing enough, flexible enough, and wise enough not to undermine either its physical or its social systems of support.

(Meadows, Meadows & Randers, 1992: 209)

[Sustainability is defined as] non-declining utility of a representative member of society for millennia into the future.

(Pezzey, 1992: 323)

Sustainability is an economic state where the demands placed upon the environment by people and commerce can be met without reducing the capacity of the environment to provide for future generations. It can be expressed as . . . leave the world better than you found it, take no more than you need, try not to harm life or the environment, and make amends if you do.

(Hawken, 1993: 209)

Sustainable development is a process of achieving human development in an inclusive, connected, equitable, prudent, and secure manner. Inclusiveness implies human development over time and space. Connectivity entails an embrace of ecological, social, and economic interdependence. Equity suggests intergenerational, intragenerational, and interspecies fairness. Prudence connotes duties of care and prevention: technologically, scientifically, and politically. Security demands safety from chronic threats and protection from harmful disruption.

(Gladwin et al, 1995a: 878)

APPENDIX 2 – MANUFACTURING COVERING LETTER AND QUESTIONNAIRE PARTS

MANUFACTURING QUESTIONNAIRE

UNIVERSITY OF SHEFFIELD

Dear

I am a Researcher at the University of Sheffield investigating the evolution of manufacturing. As the expertise needed to answer the questions is from a limited population, your responses are very valuable. The questionnaire should take approximately 30 minutes to complete. Your answers will be treated with the utmost confidentiality. The data from this questionnaire will be used, through computer simulations, to explore possible future scenarios and organisational forms. If you have any questions, or would like a copy of the aggregated results of the other company/managing directors involved, please contact me on 0114 222 7899 or by email: MEP99JSB@shef.ac.uk

Thank you for taking part

JIM BALDWIN

Guidelines

The questionnaire has been designed to explore how two characteristics interact to affect productivity, whether they have a positive, negative or neutral effect. Answer down the yellow and white columns. Keep one characteristic in mind and then compare the other characteristics as you proceed down the columns. Fill in the appropriate box with a:

+ **if together they have a positive effect (e.g. productivity is facilitated)**

O **if together have no effect whatsoever (neutral)**

- **if together they have a negative effect (e.g. productivity is inhibited)**

9 **if you are not familiar with one or both of the characteristics**

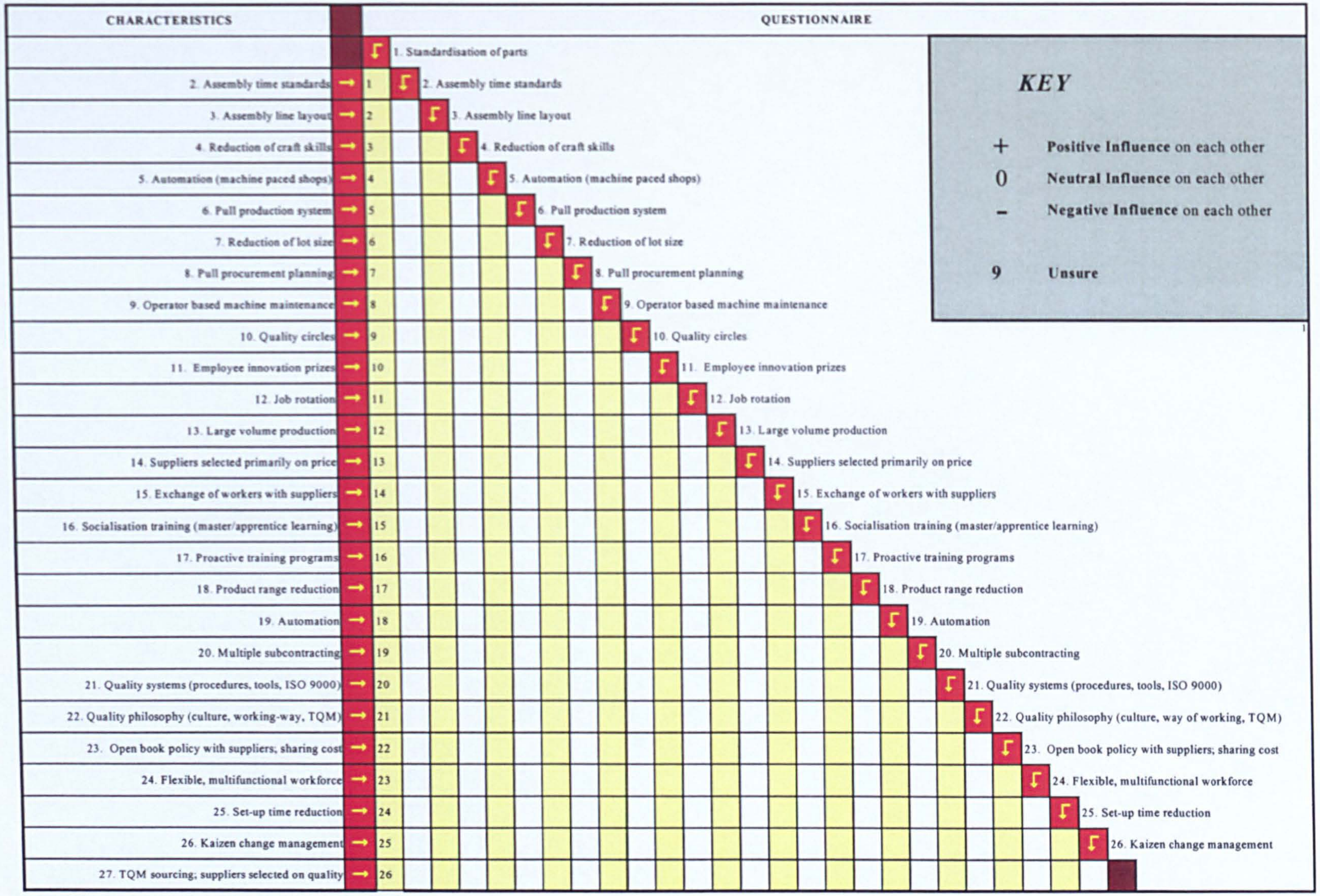
Please do not leave any boxes empty

Example:

CHARACTERISTICS								
		┌	1. Standardisation of parts					
2. Assembly time standards	→	+	┌	2. Assembly time standards				
3. Assembly line layout	→	0	+	┌	3. Assembly line layout			
4. Reduction of craft skills	→	+	-		┌	4. Reduction of craft skills		
5. Automation (machine paced shops)	→	-				┌	5. Automation (machine paced shops)	
6. Pull production system	→	0					┌	6. Pull production system

Contact: J S Baldwin, Ibberson Centre, Dept. of Mechanical Engineering, University of Sheffield, Mappin Street, Sheffield. S1 3JD. **Tel**: 0114 2227899 **Fax**: 0114 2227798 **Email**: MEP99JSB@sheffield.ac.uk

Please turn over for the questionnaire



CHARACTERISTICS

QUESTIONNAIRE

CHARACTERISTICS	
2. Assembly time standards	1
3. Assembly line layout	2
4. Reduction of craft skills	3
5. Automation (machine paced shops)	4
6. Pull production system	5
7. Reduction of lot size	6
8. Pull procurement planning	7
9. Operator based machine maintenance	8
10. Quality circles	9
11. Employee innovation prizes	10
12. Job rotation	11
13. Large volume production	12
14. Suppliers selected primarily on price	13
15. Exchange of workers with suppliers	14
16. Socialisation training (master/apprentice learning)	15
17. Proactive training programs	16
18. Product range reduction	17
19. Automation	18
20. Multiple subcontracting	19
21. Quality systems (procedures, tools, ISO 9000)	20
22. Quality philosophy (culture, working-way, TQM)	21
23. Open book policy with suppliers; sharing cost	22
24. Flexible, multifunctional workforce	23
25. Set-up time reduction	24
26. Kaizen change management	25
27. TQM sourcing; suppliers selected on quality	26

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KEY

+	**Positive Influence** on each other
0	**Neutral Influence** on each other
-	**Negative Influence** on each other
9	**Unsure**

QUESTIONNAIRE

	1. Standardisation of parts	2. Assembly time standards	3. Assembly line layout	4. Reduction of craft skills	5. Automation (machine paced shops)	6. Pull production system	7. Reduction of lot size	8. Pull procurement planning	9. Operator based machine maintenance	10. Quality circles	11. Employee innovation prizes	12. Job rotation	13. Large volume production	14. Suppliers selected primarily on price	15. Exchange of workers with suppliers	16. Socialisation training (master/apprentice learning)	17. Proactive training programs	18. Product range reduction	19. Automation	20. Multiple subcontracting	21. Quality systems (procedures, tools, ISO 9000)	22. Quality philosophy (culture, way of working, TQM)	23. Open book policy with suppliers; sharing cost	24. Flexible, multifunctional workforce	25. Set-up time reduction	26. Kaizen change management
28. 100% inspection/sampling																										
29. U-shape layout																										
30. Preventive maintenance																										
31. Individual error correction; products are not rerouted to a special fixing station																										
32. Sequential dependency of workers																										
33. Line balancing																										
34. Team policy (team motivation, pay and autonomy)																										
35. Toyota verification of assembly line (TVAL)																										
36. Groups vs. Teams																										
37. Job enrichment																										
38. Manufacturing cells																										
39. Concurrent engineering																										
40. ABC costing																										
41. Excess capacity																										
42. Flexible automation for product versions																										
43. Agile automation for different products																										
44. Insourcing																										
45. Immigrant workforce																										
46. Dedicated automation																										
47. Division of labour																										
48. Employees are system tools and simply operate m/c's																										
49. Employees are system developers; if motivated they can solve problems and create value																										
50. Product focus																										
51. Parallel processing																										
52. Dependence on written rules; unwillingness to challenge rules as the economic order quantity																										
53. Further intensification of labour; employees are part of machine and will be replaced by one																										

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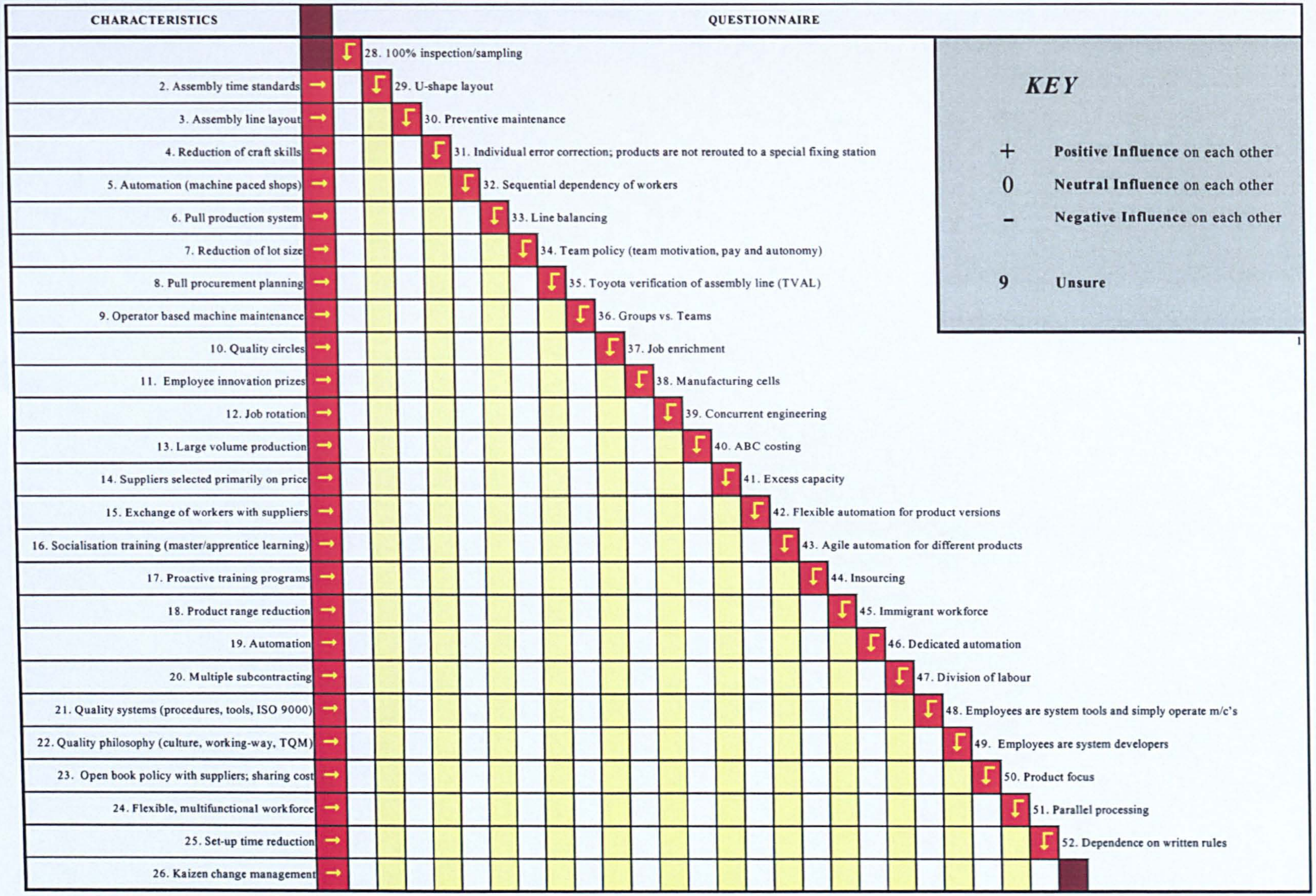

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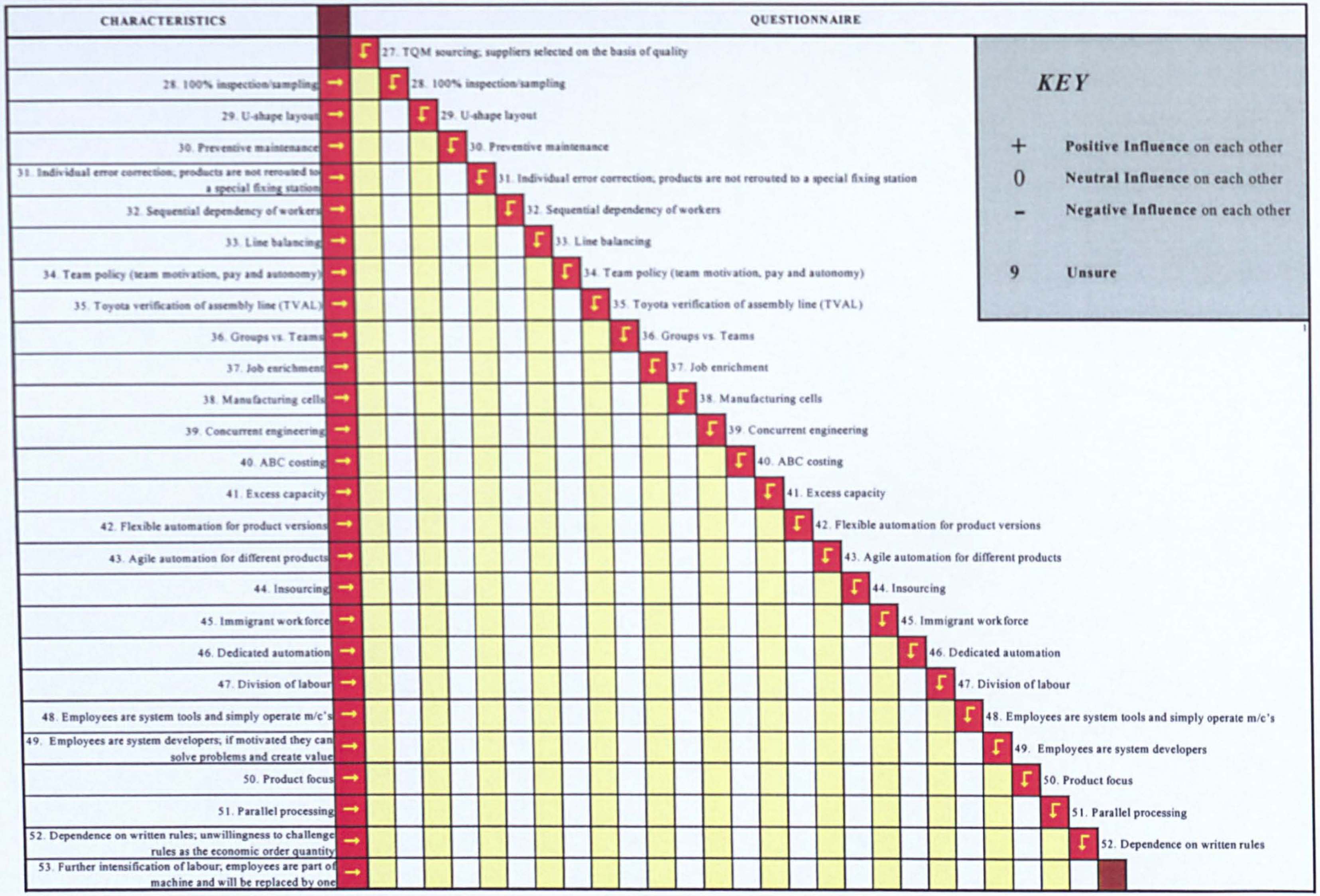

CHARACTERISTICS

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QUESTIONNAIRE

27. TQM sourcing; suppliers selected on the basis of quality
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APPENDIX 3 –PROGRAM FOR EVOLUTIONARY MODEL OF MANUFACTURING

```
'heights
Dim P(53), oldp(53),dp(53), b(53), fi(53), oldfi(53)
screen 9
view (0,0)-(639,349)
window (0,0)-(5000,5000)
dim sum(53),totp(53),oldsum(53)
dim sym(53,53),dist(53,53),hyp2(53,53)
open "pops" for output as #8
open "clad1" for output as #9
locate 1,20
print "CO-EVOLUTIONARY EMERGENCE"
locate 2,2
print "BEHAVIOURS SHAPE SELECTION"
locate 3,2
print "SELECTION SHAPES BEHAVIOURS"
locate 4,2
print "A COMMUNITY EMERGES"
'locate 5,2
'print "that have an overall mutual synergy"
'locate 6,2
'print "The model shows a fitness landscape profile that depends"
'locate 7,2
'print "on the populations present. As the populations adapt to"
'locate 8,2
'print "the landscape, they change it. So we see a mutual co-evolution"
'locate 9,2
'print "of the populations present and the landscape they generate.
locate 10,2
print "A STRUCTURAL ATTRACTOR EMERGES"
locate 11,2
input "Continue";kij

locate 13,2
input "Number to choose random series";seed
randomize(seed)
kuk=int(10*rnd)
for ev= kuk to kuk '30  '2 '20
seed = ev 'int(100*rnd)
randomize(seed)
for k = 1 to 53
p(k)=0
next k
f = .99
b= .1
m = .03
totp = 1
N= 40
dt = .01
ro= 1 '.08 '.03
r1= .8
tott =15000
infr=15001
'locate 14,2
'input "Strength of secondary interactions, 0-2";fr
'locate 14,2
```

```
'INput "Run for how long";tott
'locate 15,2
'input "Choose % of Exploration 1-100";f
f=0 '.5 '.1
f = (100-f)/100
fo=f
'locate 16,2
'input "Start Point 1-53";pp
'for j=1 to 53
'p(j)=1
'next j
pp=1
p(pp)=5
p(2)=5
p(3)=5
p(4)=5
p(5)=5
p(6)=5
'p(7)=5
'p(8)=5
'p(9)=5
'p(10)=5
'p(11)=5
'p(12)=5
p(13)=5
p(14)=5
'p(15)=5
p(16)=5
'p(17)=5
'p(18)=5
'p(19)=5
p(20)=5
'p(21)=5
'p(22)=5
'p(23)=5
'p(24)=5
'p(25)=5
'p(26)=5
'p(27)=5
'p(28)=5
'p(29)=5
p(30)=5
'p(31)=5
p(32)=5
'p(33)=5
'p(34)=5
'p(35)=5
'p(36)=5
'p(37)=5
'p(38)=5
'p(39)=5
'p(40)=5
'p(41)=5
'p(42)=5
'p(43)=5
'p(44)=5
'p(45)=5
p(46)=5
p(47)=5
p(48)=5
'p(49)=5
p(50)=5
```

```
'p(51)=5
p(52)=5
'p(53)=5

'for u=1 to 53
'p(u)=1
'next u
'locate 16,2
'input "Viability of Innovants %";vv
'vv=vv/100
vv=1 '.5
fr=2.5
for h = 1 to 53
     b(h) = b '*(1+.8*(rnd-.5))
next h
cls

open "pairmat.csv" for input as #7
for k = 1 to 53
for h = 1 to 53
input #7, sym(k,h)
next h
next k
close #7
sumsym=0
for h = 1 to 53
for k = 1 to 53
sym(h,k)=sym(h,k)-.3
sym(h,k)=1.5*sym(h,k)
sumsym=sumsym+abs(sym(h,k))
next k
next h
avsym=sumsym/53/53
locate 2,2
print "avsym";avsym
'input " ";kss
for h = 1 to 53
for k = 1 to 53
'sym(h,k)=2*sym(h,k)/avsym
'print h,k,sym(h,k)
next k
next h
cls
goto 777
locate 23,10
print sumsym
for h = 1 to 20
          for k = h to 20
          hyp2(h,k)=sym(h,k)*sym(k,h)
     if sym(h,k) < 0 and sym(k,h) < 0 then
     hyp2(h,k) = -hyp2(h,k)
     end if
     locate k,h*4-3
     print int(hyp2(h,k)+.5)
          next k
next h
delay 2
cls
for h = 1 to 20
          for k = h to 20
          if hyp2(h,k) > 2 then
          locate h,3
```

```
            print h;k;int(hyp2(h,k)+.5)
        end if
        if hyp2(h,k) < -2 then
        locate h,40
        print h;k;int(hyp2(h,k)+.5)
        end if
            next k
  next h


  delay 2
  cls

  777 line (10,5000)-(10,10)
  line (10,10)-(4990,10)
  'line (10,3000)-(2500,3000)
  'line (2500,3000)-(2500,10)
  line (4990,10)-(4990,5000)
  line (10,5000)-(4990,5000)
  'line (10,4500)-(4990,4500)
  'line (10,3500)-(4990,3500)
 locate 4,26
 print "Activity of each type"
 locate 8,7
 print "Selection Landscape"
           gj=1
                     for i=1 to 53
                               for j=1 to 53
                               'if j-i<10 then
                               'dist(i,j)= j-i
                               'else
                               dist(i,j)= abs(j-i)
                               'end if
                               'dist(j,i)=dist(i,j)
                  next j
                     next i
       locate 2,2
           print "TIME ="
           locate 3,2
           print "Ev";ev
           locate 4,2
print "seed";seed
           locate 2,17
           print "ACTIVITY ="
           locate 2,35
       print "SYNERGY/IND ="
       locate 2,60
       print "COMP/IND ="
Line (4000,1010)-(4999,1010)
      line (4000,1010)-(4000,3000)
locate 19,66
print "Total Activity"
'Locate 14,70
'print "Av Colour"

'MAIN TIME LOOP
for t = 1 to tott

if t/infr = int(t/infr) then
          maxsum=0
      for j = 5 to 53
          if maxsum < sum(j) then
```

```
          maxsum=sum(j)
          jmax=j
          end if
          next j
      'locate 11,2
      'input "New";kp
      'p(kp)=1
          kp=int(53*rnd)
          p(kp)=2
          'locate 4,2
          'print "Test";jmax 'kp
          'if p(jmax)< .5 then
          'p(jmax)=.5
          'else
          'if p(kp)<.5 then
          'p(kp)=1
          'end if
          locate 4,2
          print "Test";kp
          'end if
end if



          sum(1)=0
          totp(1)=0
                    for h = 1 to 53
                    sum(1)=sum(1)+sym(1,h)*P(h)/(1+ro*dist(1,h))
          totp(1)=totp(1)+P(h)/(1+r1*dist(1,h))
                    next h
          dp(1)=(b(1)*f*P(1)*(1+.01*p(1))+.5*vv*(1-f)*(b(2)*P(2)))*(1+.2*sum(1))*(1-totp(1)/N) -
m*P(1)

                    for h = 2 to 52
                    sum(h)=0
                    totp(h)=0
                              for k = 1 to 53
                              sum(h)=sum(h)+sym(h,k)*P(k)/(1+ro*dist(h,k))
                              totp(h)=totp(h)+P(k)/(1+r1*dist(h,k))
                              next k
                    gj=-gj
                    dP(h)=(b(h)*f*P(h)*(1+.01*P(h)) +.5*vv*(1-f)*(b(h-1)*P(h-1)+b(h+1)*P(h+1)))*_
                    (1+.2*sum(h))*(1 - totp(h)/N)- m*P(h)
                    next h
          sum(53)=0
          totp(53)=0
                    for h = 1 to 53
                    sum(53)=sum(53)+sym(53,h)*P(53)/(1+ro*dist(53,h))
                    totp(53)=totp(53)+P(53)/(1+r1*dist(53,h))
                    next h
          dp(53)=(b(53)*f*P(53)*(1+.01*p(53))+.5*vv*(1-f)*(b(52)*P(52)))*_
          (1+.2*sum(53))*(1-totp(53)/N) - m*P(53)
          totp=0
                    for h = 1 to 53
                    dp(1)=dp(1)+.02
                    'dp(2)=dp(2)+.02
                    'dp(3)=dp(3)+.02
                    'dp(4)=dp(4)+.02
                    P(h) = P(h) + dP(h)*dt
                    totp=totp+P(h)
                    if P(h)<0 then
                    P(h)=.000001
```

```
                     end if
                     next h


           locate 2,8
           print ;t

           locate 2,29
           print using "###.";totp
           if t/20 =int(t/20) then 'goto 44
           'goto 55
           symbio=0
             tsum = 0
                     for j= 1 to 53
                     symbio=symbio+ P(j)*sum(j)
                     comp=comp+ totp(j)
                     next j
                     symbio=symbio/totp
                     comp = comp/totp^2
       locate 2, 49
       print using "###.";symbio
           locate 2,70
       print using "###.#";comp*100
           'goto 88
           for k= 1 to 53
      u = k
      if u/16=int(u/16) then
      u = k+4
      end if
           fi(k)=p(k)
           if fi(k) > 29 then fi(k) = 29
           line (100+(k-1)*50,100)-(100+k*50,100+oldfi(k)*100),0,bf '(t+1000)/500 ',bf
           line (100+(k-1)*50,100)-(100+k*50,100+fi(k)*100),u,bf '(t+1000)/500 ',bf
           line (100+(k-.5)*50,2000+b(k)*oldsum(k)*20/b)-
(100+(k+.5)*50,2000+b(k+1)*oldsum(k+1)*20/b),0
           line (100+(k-.5)*50,2000+b(k)*sum(k)*20/b)-
(100+(k+.5)*50,2000+b(k+1)*sum(k+1)*20/b),3'15
'      line (2700+2000*(t+10)/tott, 100+comp*500)-(2700+2000*t/tott, 100+oldcomp*500),10
      oldtotp=totp
          oldcomp = comp
      oldsymbio = symbio
          oldfi(k)=fi(k)
          oldsum(k)=sum(k)
          next k
          Line (4000+990*t/tott,1000+10*totp)-(4000+990*(t+10)/tott,1000+10*oldtotp),9
      'goto 67
'if t/50 = int(t/50) then
hh=0
locate 5,1
print "                                    "
for k = 1 to 53
          gh=k
          if p(k)> 2 then 'p(k)=hh
          'locate 5,1+hh*3
          'print k
          hh=hh+1
      end if
          h=54-k
          fg=h
          if gh/16=int(gh/16) then
          gh=gh+4
          end if
```

```
            if fg/16=int(fg/16) then
            fg=fg+4
            end if
'           for u=1 to 10*int(p(k))
'           pset (4400+300*rnd,1600+300*rnd),gh
'           next u
'           for u = 1 to 10*int(p(h))
'           pset (4400+300*rnd,1300+300*rnd),fg
'           next u
  next k
  end if
  if t/100=int(t/100) then
  for k = 1 to 53
  write #9,p(k)
  next k
  end if
  next t
 'hh=0
  for k = 1 to 53
            'if p(k)> 2 then 'p(k)=hh
            write #8, p(k)
            'hh=hh+1
       'end if
  next k

  next ev
 'write #8, seed


 close #9
 close #8
 input "Cont";mnb
           cls
             locate 2, 35
             Print "PAIR AND SELF SYMBIOTS"
                     For h = 1 to 55
                               for k = h to 55
                               if h/5=int(h/5) then
                 locate 23,h
                               print h
                      if k/5=int(k/5) then
                               locate 24-2*k/5,1
                               print k
                               end if
                               end if
                    next k
                    next h
                    for h = 1 to 55
                    for k = h to 55
                               if sym(h,k) < 0 and sym(k,h) < 0 then
                               sym(k,h)=-sym(k,h)
                    end if
                    if 400*p(h)*p(k)*sym(h,k)/(totp^2) >3 then
                               Line (100+70*h,500)-(100,590+78*k)
'10000*P(h)*P(k)*sym(h,k)*sym(k,h)/totp^2,13
                               end if
                    next k
                    next h
'         input "next";ne
'delay 10
end
```