Cranfield University

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**Environmentally Conscious Design:
An Economic Life Cycle Approach**

School of Industrial and Manufacturing Science

Ph.D. Thesis

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ABSTRACT

Companies are under increasing pressure to deal with environmental concerns during product design, for it is the design process which primarily decides the environmental impact of a manufactured product over its life. Tools which assist in taking a life cycle view of the product are a necessary support to designers. Prime amongst these tools is Life Cycle Assessment (LCA). However, a major criticism of LCA methodologies is that while they provide advice on environmentally superior product designs, they do not provide guidance on the economic impact. With product take back increasingly likely to become the responsibility of producer companies attention is now being paid to the later phases of a products life, such as maintenance and disposal costs. A new methodology is shown to be required to complement LCA, one which considers the economic implications of environmentally superior designs over the whole product life.

It is argued that a major challenge of such a methodology will be how it deals with the uncertainty associated with the future. The research provides a review of product life cycle design methodologies and a critique of existing approaches to uncertainty. A design teams requirements for decision support that deals with product economic life cycle uncertainty is presented and a decision support methodology which meets these requirements is described. The methodology builds upon the theory of life cycle costing. In practice, the methodology integrates a computer based life cycle model with statistical techniques to quantify the contribution of life cycle variables. In bringing these proven but previously separate tools together the method resolves the issue of uncertainty in a novel and acceptable way.

Through the use of an in-depth industrial case study, it is shown that the methodology provides practical support to the design team to produce economically superior product life cycle designs.

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AUTHOR PROFILE

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Whilst with Westland Helicopters he was involved with manufacturing systems re-design and the project definition phase of the RAF EH101 project.

At The CIMulation Centre, part of the Hawker Siddeley Group, he was a member of the team that provided industrial simulation consultancy.

He was employed by The CIM Institute where he worked on a concurrent engineering related EUREKA/FAMOS project. Following this he was employed as a Consultant with Parallax Management Consulting where he was involved with Business Process Re-engineering.

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ANOVA: Analysis Of VAriance

AMDEL: An Methodology for the Design of Economically superior Life cycles

BEAB: British Electrical Advisory Board

CE: Concurrent Engineering

DARPA: US Defense Advanced Research Projects Agency

DFA: Design For Assembly

DFDA: Design For Disassembly

DFM: Design For Manufacture

DFMA: Deign For Manufacture and Assembly

DFS: Design For Serviceability

DICE: DARPA Initiative on Concurrent Engineering

DoD: US Department of Defense

EFC: Expected Failure Cost

EOL: End Of Life

EPA: Environmental Protection Agency

EPSRC: Engineering and Physical Sciences Research Council

EU: European Union

EWO: Electronic Waste Ordinance

LCA: Life Cycle Analysis

LCC: Life Cycle Costing

LCE: Life Cycle Economic Model

NPV: Net Present Value

PV: Present Value

SE: Simultaneous Engineering

SERC: Science and Engineering Research Council

1. Research Objectives

This chapter defines the problem which forms the focus of the research, sets out the objectives of the research, establishes the research methodology and describes the research deliverable.

1.1 Problem Statement

Economic activity typically involves the use of natural resources and results in the creation of waste that the planet has to absorb. It is estimated that each day in the UK 320,000 tonnes of waste is generated, annually amounting to 120 million tonnes. Most of this waste is disposed in 3,200 landfill sites, with 8% incinerated [Cairncross 1991]. The principle of sustainable development is to reduce both usage of natural resources and creation waste. This can partly be achieved through legislation making landfill an expensive end of life (EOL) option and therefore strengthening the argument for recycling.

With impending legislation, a third of landfill sites will close in the next five years [Burke et al. 1992]. The Centre for the Exploitation of Science and Technology (CEST) have researched into disposal issues regarding motor vehicles [Williams 1991]. They note that tighter regulation has already resulted in increased disposal costs. This has been particularly noticeable for landfilling, where costs are doubling every one to two years.

The role of the consumer has been to force change upon companies. Products which are perceived by the consumer to be green are gaining market share over rival products, with 59% of consumers prepared to buy products on the basis of an ecolabel [Ecolabelling 1992]. In this atmosphere of increasing environmental awareness, some 79% of the FT-SE 100 companies produced public reports in 1996 on their environmental performance, in order to demonstrate to consumers their commitment to environmental issues [Beugge 1997]. Even if products pass through the legal and regulatory requirements, but fail to reach the acceptance levels set by the consumer, then those products risk being left on the shelf at the point of sale.

In the long term, legislation can reduce the environmental impact of manufactured products in two ways [Cairncross 1991]. Firstly by encouraging schemes such as ecolabelling, which indicate that the product is efficient in terms of energy usage and that a percentage of its components are produced from recycled material, so that consumers can make informed choices at the point of sale. Secondly at the end of the product life, by making disposal costs more and more expensive, proposals are under discussion which are likely to require manufacturers to be involved in the final destination of products [Classe 1997].

It is the current strategy of many companies to be perceived to have environmentally friendly products and/or ultimately achieve ecolabel status [Ecolabelling 1992]. One result has been an increase in the amount of recycled material used in products along with intensive marketing campaigns. With legislation aimed at making the company responsible for EOL products, some companies may experience severe financial penalties for short term design strategies that do not consider the EOL scenario. For example, Siemens estimates that product take back legislation could result in the life cycle product costs of washing machines rising by as much as 15% [Clegg 1992a]. Whereas in the past such EOL costs were borne typically by local authorities, the producing company will be responsible for these EOL costs.

Along with production costs, service costs, length of useful life, and most other product characteristics the disposability/recyclability of any product is primarily determined during its design, by the design team [Smith and Reinertsen 1991; Boothroyd 1988]. By the end of the design phase the ability to change manufacturing processes, energy sources, disposal methods, etc. is severely limited. This makes the design activity itself the prime source of opportunity for reducing both the environmental impact and increasing the profitability of a company. A design team will have to consider the potential multiple life cycles of products and components as they are reused and recycled in further product designs. As existing products become available for reuse or recycling, the design team must consider whether it is feasible both in terms of economics and physical constraints to use existing components. Decisions made today will affect environmental and hence economic performance at the end of the products life, may be 20 years into the future [Zust 1993].

Over the next 20 years the legislation dealing with products, their environmental impact and their end-of-life treatment will change [Fiksel 1993]. Legislation, consumer behaviour, costs and values, waste technology and recycling infrastructure are changing and will continue to change as the world seeks a solution to the environmental problem. Prediction of such events is fraught with uncertainty. As the legal framework moves towards producer responsibility for EOL there is increasing need for tools to provide decision support to the design process.

The above research discovered that the domestic white goods industry, which will be among the first to experience EOL product take back legislation has little experience of product take back at EOL. This leaves the domestic white goods sector the least prepared to deal with the demands of new legislation. In the majority of cases, take back schemes have been implemented without the need for incentives or legislation. It has been decided on an economic basis. However, these companies also recognise the threat of legislation and increasing landfill costs, and therefore by acting proactively believe that they will achieve a competitive advantage. As such companies continue to take back products they will have direct economic incentives to design products that are increasingly profitable over the entire product life cycle. Design is likely to play a key role in maximising this profitability of the product life cycle.

2.11 Product Design

It is shown in the following section that design plays an important part in determining the product life cycle costs. Product design is a process of synthesis in which product attributes such as cost, performance, manufacturability, safety, regulatory requirements and consumer appeal are considered and traded off against one another to arrive at a final design [Suh 1990; Jo, Parsaei and Sullivan 1993].

Research has shown that between 60% and 90% of life cycle costs, which include the cost of materials, manufacture, use, repair and disposal of a product, are determined during the early stages of design [Nevins and Whitney 1989; Gatenby and Foo 1990]. In comparison, the design process costs on average just 5% of life cycle costs [Boothroyd 1988]. Therefore product life cycle costs are established at an early stage of product development, when fundamental design choices are made [Smith and Reinertsen 1991].

An example of the influence of the design process on the profitability of product take back is provided by Canon. The company has established a toner cartridge remanufacturing facility based in China, which receives cartridges from Europe, Japan and the USA. The 2.5 million reprocessed each year represents 15% of total production. In the US, Xerox

1.2 Research Background

During the initial period of the research, a number of preliminary observations were made:

- Legislation is moving towards making manufacturers responsible for their products at the end of the products life.
- The automotive, electronics and domestic white goods markets will be among the first industries to experience such legislation.
- Some electronics and automotive manufacturers have already established product take back and recycling schemes.
- During product design there is little or no consideration within these companies of the economic implications of product take back issues.
- The greatest opportunity to influence the life cycle profitability of a product is at the early design stages.
- The use of current costs to consider the EOL scenario is a potential hazard because the future involves uncertainty about events and values.

Hence the industrial need for the research can be stated:

Design teams require a decision support methodology that provides a life cycle economic view of the product design, taking into account uncertainty involved in dealing with the future, to create economically superior products, that comply with or surpass environmental legislation.

1.3 Research Context

The context of the research is the domestic white goods sector. This was selected because the automotive, electronics and domestic white goods markets will be among the first industries to experience EOL product take back legislation. A number of electronics and automotive manufacturers have already established product take back and recycling schemes, leaving the domestic white goods sector the least prepared to deal with the demands of new legislation. However, the proactive electronics and automotive companies who have implemented product take back schemes have done so, not through environmental principles, but because it is profitable or necessary in the short term. As detailed in chapter 2, some of these companies have now begun to apply some of their experienced gained in EOL take back to the design process. Typically, the domestic white goods sector does not have the infrastructure or experience to deal with planning for product EOL. With EOL legislation moving closer and little or no history of schemes for EOL products the white goods sector is under particular pressure. With emphasis on sound financial management and concern over the uncertainty associated with the future and predicting what may happen at product EOL. Hence, white goods manufacturers have a strong requirement for methods to assist in the design of economically superior life cycles.

1.4 Research Objectives

The main objective of the research within the domestic white goods sector is:

1. to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products; by
2. undertaking a literature and industrial review; and
3. evaluating and selecting methods to meet the requirements for decision support; and
4. demonstrating that such a system is possible to construct, practicable and beneficial.

The focus of the methodology is based upon economics rather than environmental concerns. Companies tend to act where there is a clear economic advantage. The role of government is to ensure that such economic activity does not harm the environment, either by outlawing it or by placing an economic penalty on it so as to discourage such activity. Environmental legislation is based upon the polluter pays principle, however, there is a danger that the materials and energy expended in recycling may exceed the environmental problems associated with landfill.

1.5 Research Deliverable

The research deliverable is a decision support methodology which is shown to be usable by design teams within the domestic white goods industry to produce economically superior product life cycle designs.

1.6 Research Strategy

Research strategies can be classified into two distinct approaches, qualitative and quantitative. In the quantitative approach, the concepts and constructs are predetermined, whereas in the qualitative approach, concepts and constructs emerge from the data gathered and are grounded in empirical data collected through research [Bryman 1984]. The choice of research strategy and methods to use is dependant upon the research area and the extent of theorising that exists in the field [Duncan 1979].

Research on providing practical and usable support to design teams concerning economically superior product life cycles in a design environment is still in an initial stage of rapid paradigm development, and therefore a qualitative research strategy was adopted. The development of the field can be measured by a survey conducted in 1992 through the world-wide members of CIRP, for research findings in the areas of design for disassembly and recycling produced six responses from Europe, one from Japan and one from the USA [Boothroyd and Alting 1992]. However, the International Conference on Engineering Design (ICED) has, since 1993, had a section devoted to environmentally conscious design issues [ICED 1993]. The major focus in qualitative research has been on data collection rather than data analysis, because "qualitative data are themselves extremely complex and not readily convertible into standard measurable units of objects seen or heard..." [Schatzman and Strauss 1973]. However, this does not necessarily mean that inferences cannot be drawn from the analysis, as stated by Jones "the analysis of qualitative data is a process of finding and making a structure in the data, and of giving this meaning and significance....The kind of structure the researcher looks for depends upon the purpose of the enquiry...." [Jones 1985; McCracken 1988].

The research strategy employed focused on regular visits and literature reviews of academia and industrial organisations who have followed or examined EOL strategies. This approach was adopted because the subject of EOL product take back is a rapidly evolving area; and there are only a small number of companies involved in such EOL activities. Hence, any new developments were monitored and their impact upon industrial organisations examined. Such an approach had the disadvantage of not allowing any statistical generalisations to a larger industrial population [Bresnen 1988]. This strategy allowed observation at first hand of the EOL process so that the researcher could obtain an understanding of the issues involved from a practical perspective.

1.7 Research Methodology

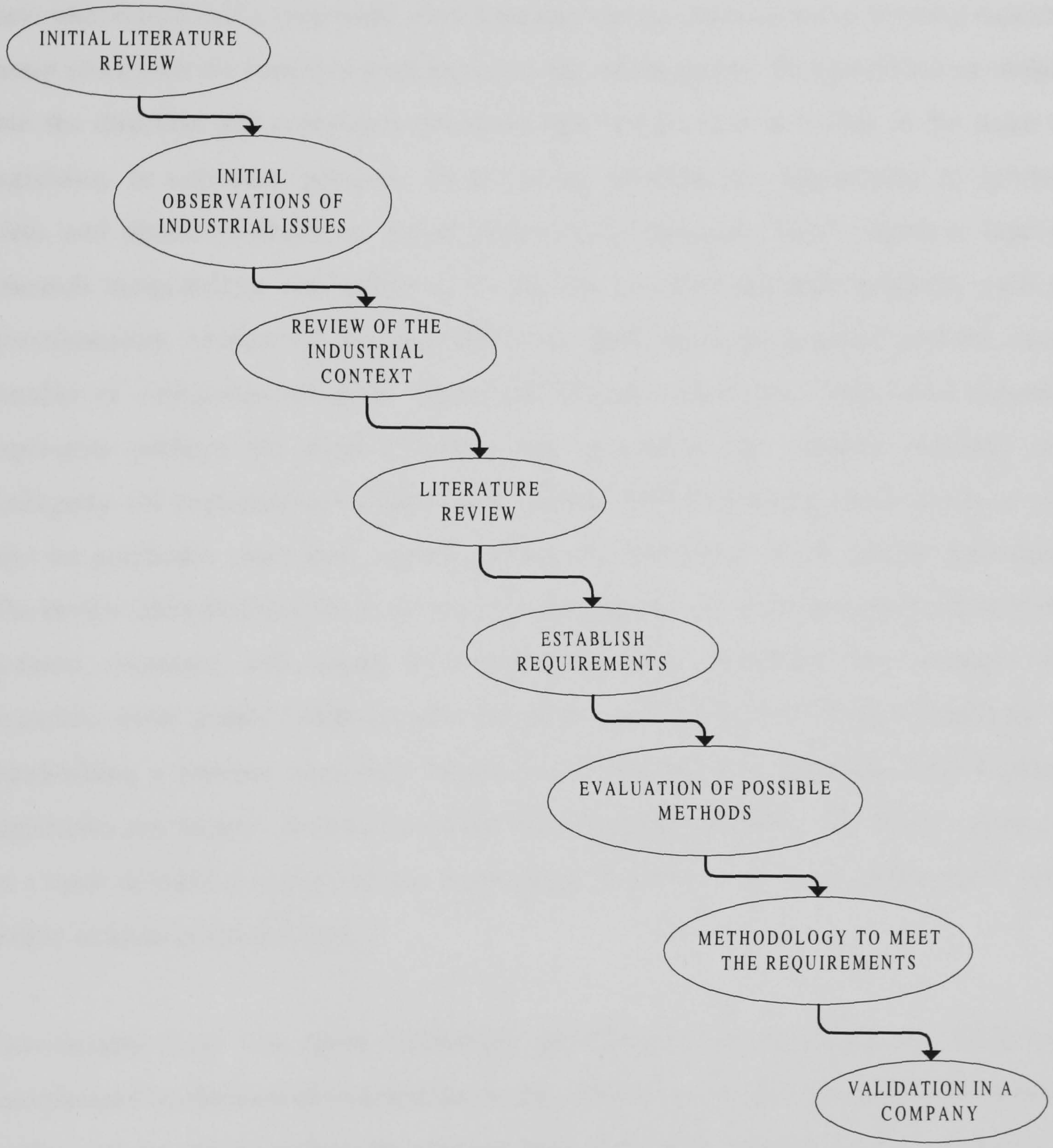

Figure 1.1: Research methodology

After an *initial literature review* of 3 months, a number of observations were established, which are detailed in section 1.2. These *observations of industrial issues* identified a number of trends and led to a review of the industrial context of the research. The *review of the industrial context* examined initiatives in the automotive, computer and electrical goods industries. Over 10 companies who are best practitioners of product take back were visited and included ICL, DEC, Ford, Nissan and Rover. Environmental forums were held with structured group discussions to develop industry group consensus on concerns with regard to the environment. This provided an insight into the direction that companies perceived they would have to follow in the wake of legislation or consumer pressure. Such forums provided the opportunity to validate ideas and obtain feedback on the direction of the research. This qualitative type of research methodology was preferred to the use of other research methods, such as questionnaires, because of the diversity of the EOL strategies adopted and the small number of companies involved. Carter and Cannon state that, "first hand accounts represents perhaps the most effective way to convey the richness, subtlety and ambiguity (of experiences)" [Carter and Cannon 1992]. However, such accounts can also be politically motivated, biased and non-representative of the whole population. The review identified the domestic white goods industry as the industry that required the greatest assistance with regard to product take back legislation. For example, the domestic white goods company involved in the case study had already committed to establishing a product take back centre in the UK and was concerned that German legislation my require them to take back their exported products. The observations led to a more detailed *literature review* focused on the area of life cycle design tools, both within academia and industry.

Considerable time was spent conducting an extensive *literature review* which was complicated by the lack of material due to the immaturity of the area. The main purpose of this activity was to review the existing type of decision support used by members of the design team to create economically superior designs. Publications, seminars and conferences which focused on the use of life cycle design tools were examined.

The first four stages, detailed above, identified that design teams require decision support on the economic life cycle during product design. To *establish requirements* of such support, the research developed a scenario of the design process by which design teams would arrive at economically superior designs. This method of establishing the requirements was chosen because the subject area is in its developmental stages. The use of such a technique, in the context of exploratory research, is described by Goffee and Scase [Goffee and Scase 1985]. It was not possible to conduct an observation based study of the design process that considers the economic implications of environmentally conscious design due to a lack of industrial practice.

The set of requirements provided a guide for a detailed *evaluation of possible methods* that might meet the set of requirements established from the design scenario. A number of different methods were identified that did meet the requirements and these were evaluated in order to determine their suitability. In practice, although some methods initially seemed promising, on careful evaluation they only met some of the requirements and were therefore not taken further. This evaluation of possible methods led to a number of components, which could potentially meet all the requirements that were derived from the design scenario. The next stage of the of the research was to integrate these methods to form a methodology to meet the requirements. If the methods could not work together, then alternatives would have had to be sought. However, the methods were successfully integrated allowing the next stage of the research, which was to undertake industrial *validation in a company.*

The context of the research is the domestic white goods industry and the users of the methodology the design team. The company selected for the case study was one of the world's leading producers of domestic white goods, who were concerned with the impact that new EOL product take back legislation could have on their business. The methodology, in the form of a prototype, was applied to a product range. To assist in its implementation, the researcher spent a considerable amount of time with the company, assisting and supporting the company in the application and the results of the methodology. This had the benefit of providing direct observation on the use and acceptance of the methodology within the company. Hence, the validation of the methodology was obtained from such observations and the evidence of its continued application within the company.

1.8 Thesis Structure

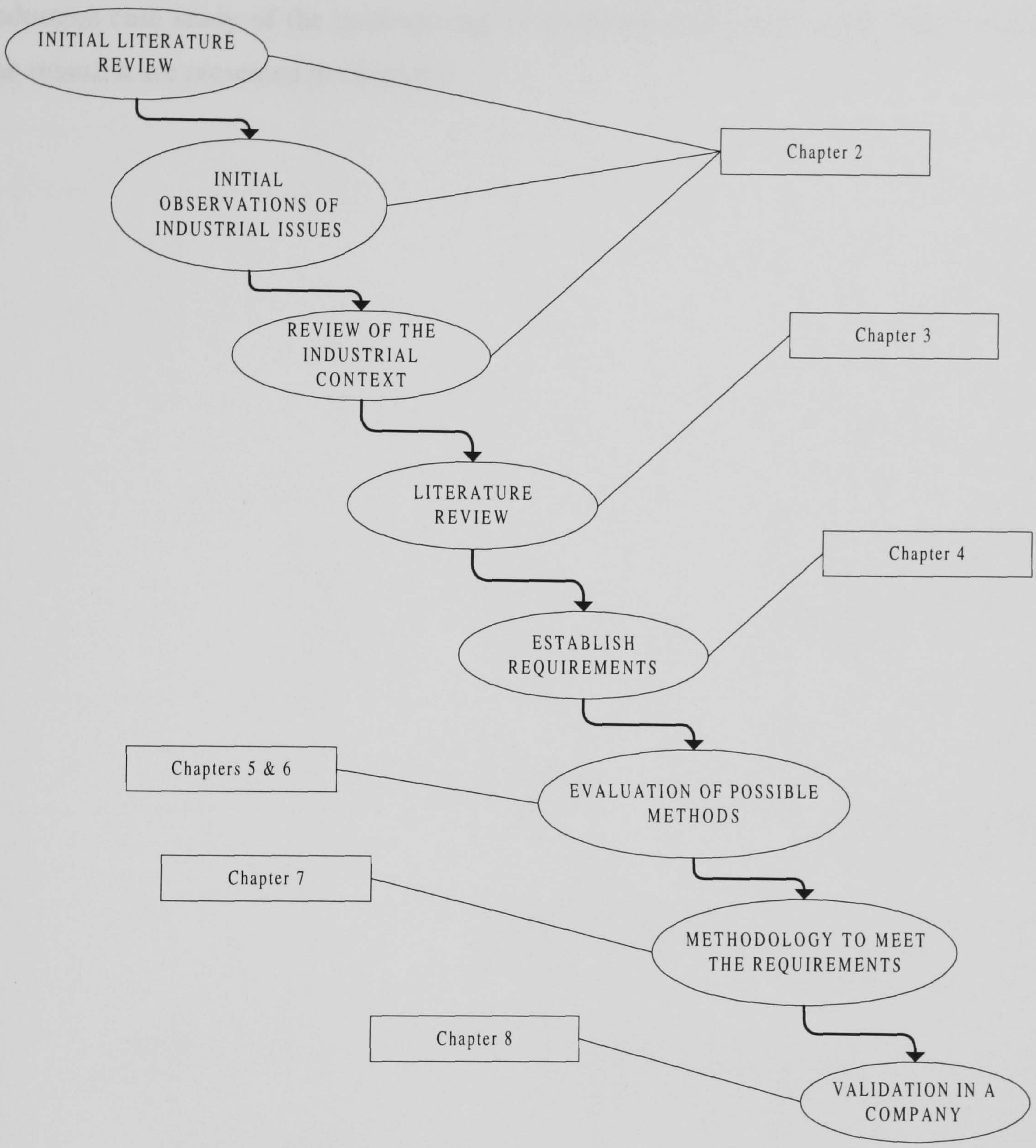

Figure 1.2: Thesis structure

Figure 1.2 demonstrates how the individual chapters of the thesis relate to the research methodology. Chapter 2 establishes the industrial need for the research, examining techniques, industries, issues and pressures. A review and critique of current literature is presented in chapter 3. This is followed in chapter 4 by a design scenario in order to determine a set of requirements to meet the objectives and deliverables of the research.

Chapters 5 and 6 discuss the evaluation of possible methods to meet the requirements set out in chapter 4. Chapter 7 describes the elements of the methodology, whilst an industrial case study of the methodology is described in chapter 8. The conclusions of the research are presented in chapter 9.

2. Introduction

The area of research is introduced by discussing the world's dwindling natural resources and the responses of society and manufacturers. The author provides context in this broad and fast changing subject area by explaining some of the major forces acting on the problem.

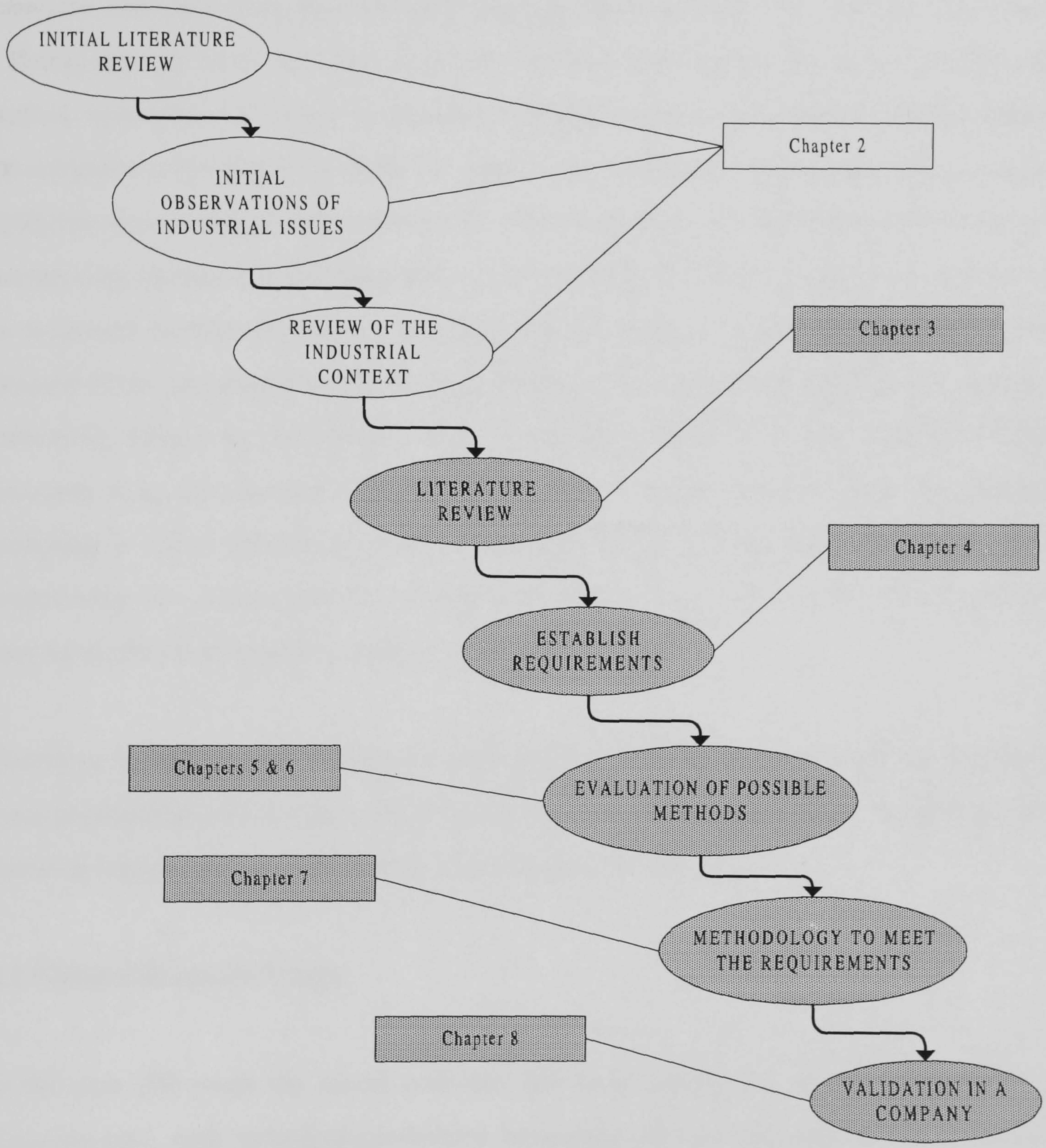

Figure 2.1: Relationship of chapter to research methodology

The chapter shows that material resources are becoming evermore scarce and that product take back is seen as an important option in addressing this problem. Emphasis is being placed on the original manufacturers reclaiming value added during the production of the product. Issues which effect the economics of the product life cycle, such as take back legislation, technology and product design are examined in detail. It is shown through industrial case studies that such legislation has the potential to impose a serious financial strain on companies. Furthermore, evidence is provided through additional case studies of proactive companies who have already established product take back and who are making a financial profit from such activities. Such examples demonstrate that in some industry sectors, where there is a clear economic advantage, the lack of legislation will not hamper the adoption of product take back. In some cases, companies are shown to be using the design process to design their products for increased life cycle profitability. However, it is not necessarily true that the opportunity is being realised. The life cycle of a product can be measured in years and there is a possibility that companies will not take back at EOL because of the uncertainty associated with future events, such as bankruptcy or a change in ownership. Hence, the designing of extra value into a product, in order to achieve higher economic long term returns at EOL, may be viewed as a liability and result in companies accepting a lower short term profit. Furthermore, those personnel responsible for the profitability of a design may be adverse to long term gains, when in ten years time they may have retired or moved to another company.

Therefore the author demonstrates the importance of product design in determining the life cycle profitability and the lack of a single methodology that provides the design team with decision support on the design of the whole economic life cycle.

2.1 Natural Resource Usage

In the past 100 years the world economy has been consuming natural resources at an alarming rate, with industrial production increasing 50 fold [Rostow 1978]. In the US, more than 10 tons (20,000 lb) of active material per person is extracted each year [Ayres 1989; Ayres 1975; Ayres 1974]. Active material is defined as including food, fuel, forestry products, ores and non metallics. The majority of this active material, 94%, is converted into waste within months of being extracted. The remaining 6% is embodied in durable goods. [Ayres 1989]

Growth in the depletion of natural resources is predicted to continue and by 2050 the world population is expected to have doubled [UN 1992]. In addition it is further estimated that the global economy required to meet this population and hence demand for natural resources could be five times its current size [Heaton et al. 1991]. Table 2.1 demonstrates the estimated lifetimes of global resources in years, both at current and predicted future rates. The table shows that even at current consumption rates and with increased extraction technology, the supply of natural resources is limited in most cases to no more than 300 years. Even with the latest recycling technology, which for the majority of cases does not allow for 100% recovery of resources, the world is faced with a serious problem unless more dramatic developments occur.

	CURRENT CONSUMPTION		PREDICTED 2030 RATES[1]	
	RESOURCES[2]	RESERVES[3]	RESOURCES[2]	RESERVES[3]
Aluminium	256 years	805 years	124 years	407 years
Coal	206 years	3,226 years	29 years	457 years
Cobalt	109 years	429 years	10 years	40 years
Copper	41 years	277 years	4 years	26 years
Molybdenum	67 years	256 years	8 years	33 years
Nickel	66 years	163 years	7 years	16 years
Platinum	225 years	413 years	21 years	29 years
Petroleum	35 years	83 years	3 years	7 years

[1] Assuming population of 10 billion consumes at current US rates
[2] Quantities that can be extracted using current technology
[3] Total quantities thought to exist

Table 2.1: Estimated lifetimes of global resources (years) [Cairncross 1991]

Therefore the reduction in the depletion of natural resources must be achieved at least in part by sustainable development and recycling.

2.2 Materials

Whilst the need for sustainable development is clear, there is a growing trend amongst manufacturers to use composite materials, which while being more advantageous during manufacture are in many cases at odds with recyclability. The use of materials in manufacturing has changed, see Table 2.2, not only in terms of the relative amounts of different materials, but also in the variety of materials available. At the turn of the century, US industry used about 20 elements of the periodic table, now virtually all naturally occurring 92 elements are used [Materials and Man's Needs 1975].

	1900	1940	1989
Metals and Non-metallics	26%	27%	48%
Organics	1%	5%	11%
Forestry Products	50%	30%	23%
Agricultural, Fishery and Wildlife Products	23%	38%	18%

Table 2.2: % US raw material consumption (1900-89) [US-OTA 1992]

Advances in structural materials has led to the development of ceramics and composites that offer superior performance, such as high temperature strength, high stiffness and low weight, compared with traditional materials such as aluminium [US-OTA 1992]. For example, telecommunications cables produced in the 1960's consisted mainly of steel, lead and copper with less than 10% consisting of aluminium and plastics. However, by the 1980's, the plastic composition of the cable had increased to 35%, with the lead content at 1%. The reduction of lead resulted in companies, such as AT&T the US telecommunications company, achieving substantial savings in the order of millions of pounds annually. Currently the equivalent of 2,000 pounds of copper can be replaced by

65 pounds of fibre optic, with the energy requirements to produce a fibre optic being 5% of that required for copper [Coloumbo 1988].

The above figures demonstrate the way in which the use of materials has changed. In addition advances in chemistry, materials science and joining technology have resulted in new methods to combine materials in new ways, such as anti corrosion coatings on metals, or fibre reinforced composites. This new technology allows the production of products which are cost effective to produce but are materially complex and often extremely difficult, if not impossible to recycle. For example, cars are composed of a vast array of different materials, including high-strength steel, aluminium, copper, ceramics, metal matrix composites and more than 20 different types of plastics [Field 1991]. A further example of such a phenomena, is a modern crisp packet, see Table 2.3. The packet comprises of nine layers of differing materials that produce a lightweight package which meets requirements such as preserving freshness, indicating tampering and providing product information, but does not facilitate recyclability [Coppe 1992].

MATERIAL LAYERS
Copolymer
Polypropylene
Copolymer
Inks
Polyethylene
Aluminium Metalisation
Copolymer
Polypropylene
Copolymer

Table 2.3: Cross section (0.05 mm thick) of a crisp packet [US-OTA 1992]

These examples demonstrate that the use of new materials, such as composites is increasing. The use of such materials is driven by economic logic, however, many are difficult if not impossible to recycle.

2.3 Product Life Extension

As an alternative to using such composite materials to create new products, there may be an economic argument for extending the life of existing products, thereby reducing the use of new materials, such as composites. However, there are few economic cases, where such an argument holds true, especially where consumers demand the latest technological advances in products. For example, refurbishment of a washing machine may lead to the life of a product being extended four fold, from 5 to 20 years, thereby reducing the need for resources to produce three new products. However, consumers tend to want change with additional features which often lead to increased performance and reduced operating cost. Furthermore, the increased performance may lead to a reduction in the power consumed by the product providing an environmental benefit in terms of reduced natural resource consumption and emissions by power stations.

Typically, complex products have high repair costs and these prompt customers to purchase new products, rather than having the expense of repairing products [ChemCycle 1991]. However, where the cost of product replacement is high, such as in the commercial aerospace business, product life extension has proven to be economically viable. By extending the life of a product, the need for natural resources diminishes. Examples of products where life extension has been successful include Linn music systems who have developed a modular system that allows up-grade; Japanese railways who remanufacture trains every 3-4 years; Cathay Pacific and Rolls Royce who have signed an agreement to upgrade in-service aero engines with the latest enhancements as they are developed; the London Routemaster bus which through ease of maintenance has outlasted its successor; and defence equipment which is regularly upgraded with new "eyes and teeth". As a demonstration of increasing product complexity and decreasing life cycles, a washing machine in the 1920s had a life of 20 years, whereas in 1993 the average washing machine has a life of 7 years. This is often due to the failure of a component which is uneconomic to repair [Puttick 1993].

By extending the life of existing products, the value to the owner is retained and the need to use composite materials, which are difficult to recycle, reduced. However, there are only a few categories of products for which this approach is economically viable.

2.4 Recycling

If extending the product life cycle is not a viable option for sustainable development, then the use of recycling should be considered. The following sections examine the economics of recycling, and also the influence of technology and the rising costs of landfill which will strengthen the economic argument for recycling. The European Community Environment Council has defined recycling in its 1993 packaging directive (Article 6 of EC Directive 94/62/EC) as reusing waste material in some form [Classe 1997]. Thus granulating a plastic PC monitor casing and reusing it to make car bumpers is recycling. However, burning the plastic as a substitute heating fuel is classified as waste recovery. Traditionally the majority of value and resources still contained within EOL products has not been recovered. EOL products at best have been shredded to recover most ferrous and non-ferrous metals [Zussman et al. 1994].

2.4.1 Economics

The principles of recycling are not new. In the past people commonly purchased food products in reusable tins or bottles. With the resulting geographical centralisation of manufacturing operations through rationalisation, the cost of returning containers became prohibitive. Where the volume of returned containers is high and the cost of recovery low then recycling persists, where it is not, then it has receded. For example, the average milk bottle in the UK is reused 12 times [Cairncross 1991; Veroutis 1991]. In Japan, two thirds of all bottles are collected and used an average of three times while beer bottles are reused an average of 20 times. Aluminium cans are gradually replacing bottles, but more energy is required to recycle aluminium than glass. However, it makes more sense to create a new can by melting down aluminium, than to mine bauxite and smelt it, as less energy (5% of the energy needed to extract raw bauxite) and cost are expended in the process. In the USA, 55% of aluminium cans are recycled and in Sweden where a deposit system is enforced 70% of all aluminium cans are recycled. In the UK, Alcan announced its first operation to recycle cans and now uses recycled aluminium in a third of its production [Cairncross 1991].

The economics of recycling are generally reliant on two factors, the logistical cost of recovering and sorting spent products; and the demand for those spent products and the cost of reprocessing. For instance, the high capital costs of reprocessing plastic means that economies of scale are important. Historically, to achieve large volumes of returned spent products such as bottles, deposit-refund schemes have been established. The consumer is then faced with a choice, return the product and receive an incentive or else abandon the product. In Sweden a deposit scheme of about 5p on PET (polyethylene tetraphthalate) bottles has resulted in a return rate of 60-70%, while experience with aluminium cans has demonstrated that a return rate of 80-90% is achieved when a deposit-refund scheme is set at 15p per can. Studies quoted in the USA suggest that such incentive schemes result in a return of 70-90% of targeted containers [US-OTA 1989].

Recycling initiatives are now being adopted for higher value added products, such as computers and cars [Williams 1994]. These higher value added products offer the best opportunities for the recovery of residual material and part value. Many companies in these sectors have active recycling and product recovery operations, with many based on service, repair and product upgrade facilities. This is demonstrated by the case studies presented in section 2.8. However, the market for spent products changes just as any other market with the advent of new technology. Therefore the following section explores the influence of technology.

2.5 Technology

Technology will alter two major aspects concerned with the product recycling. It will change the basic underlying design of products; and it will alter the basic processing tools used at EOL to reclaim materials and components. The use of product technology will however, ultimately have an impact on the use of process technology.

2.5.1 Product Technology

The use of new technology in products has resulted in a number of trends. An example is that of photocopier technology, which has largely remained unchanged over the last ten years. This has seen companies such as Xerox being able to refurbish a large number of machines. If there is a breakthrough in document scanning that produces high quality photocopiers at low cost, then it may only be economic to recover the material rather than the component value. Xerox used to refurbish typewriters, but with the advance of computer technology, this process became uneconomic [McAloone 1993].

An objective of car manufacturers in the 1990s, is to produce lighter cars which conserve petrol consumption and meet ever increasingly tougher legislation on emissions. Hence, car designs now contain more weight saving plastic components. This reduces the margins generated by recycling, see Table 2.4, and hence the incentive, because of a reduction in the metallic content and an increase in plastics which yield less value and are often difficult to recycle [Veldstra and Bouws 1993].

TYPICAL CAR WEIGHT	1,429 Kg
Steel Scrap Value	$135
Non-ferrous Value	$18
Fluff Value	($47)
Logistics Costs	($10)
Processing Costs	($47)
TOTAL Scrap Value	$49

Table 2.4: US scrap value of car hulks [Clark and Field 1990]

Plastics high weight to strength ratio means that a large volume has to be collected to provide a modest weight and therefore value for recycling. In addition plastic is often produced from several different resins bonded together. For instance, a liquid food container may contain one plastic on the external surfaces for appearance and strength, another in the central part for strength and a third on internal surfaces designed to resist fats and acids. Process technology is now being developed to separate different plastics, but it is uncertain when this technology will be available [Clegg and Williams 1994; Clegg 1992b].

2.5.2 Process Technology

In many industries a shredder is used to reclaim EOL material. This is a machine typically used in the automotive industry, which takes a complete car minus its tyres, radiator and petrol tank; and shreds it into small pieces. Separators are then used to sort the metallic pieces from the non metallic pieces. Time consuming and expensive manual disassembly is often a precondition to shredding in order to recover the items such as the petrol tank. Such process technology requires large throughput to operate economically. This necessitates centralised recycling plants which may result in high logistics costs. Furthermore, the material recovered from shredding is not equivalent to that of new material and hence new materials often have to blended with them to reach acceptable quality standards. The major disadvantage of shredding is that it mixes the majority of the constituent parts of a product before attempting to separate them, creating a loss of value [Zussman et al. 1994].

The advance of both product and process technology will have an impact on the economics of recycling, however such development is open to uncertainty. If the cost of disposing of EOL products is high, then the pressure to develop new process technology will be great. However, such costs are driven by a number of factors which will now be considered.

2.6 Costs of Landfill

The rising costs and scarcity of landfill sites increases the economic argument for product take back and recycling. In 1992, Americans generated over 160 million tons of municipal solid waste, with 80% going to landfill, and the remaining 20% to incineration and recycling [Clegg and Williams 1994]. The number of available landfills has declined from 18,500 in 1979 to 6,500 in 1988, with a predicted figure of 3,250 for 2000 [Biddle and Christie 1993]. America's Environmental Protection Agency (EPA) estimates that 80% of existing US landfills will be closed by 2010. This ever decreasing number has caused the cost of landfill to increase rapidly.

It is predicted that Japan will exhaust its available landfill sites by 2005. In Tokyo, the local council has been refusing to accept large items of domestic waste such as TV sets or refrigerators, because it is short on landfill capacity. The result has been that much of this waste has been dumped on Japan's northern island. To combat this issue the Japanese ministry of health and welfare has attempted to force manufacturers to take responsibility for their products [Cairncross 1991].

In Germany, the Netherlands and Italy the cost of landfill is $80-100 per ton. The "old" West Germany, who in 1988 exported 2.1 million tons of waste to East Germany have, since reunification, lost its main outlet. Figures for 1991 estimated that the German population of 80 million owned 41 million television sets with a typical life of 12 years. The annual disposal rate was estimated at 3.4 million sets per year [Clegg and Williams 1994].

The EC Commission, determined to set common standards for waste disposal facilities to avoid trans-frontier dumping has drawn up a directive [Clegg and Williams 1994]. One of the stated aims of this legislation is to encourage recycling to be economically viable through increased costs of landfill. Therefore such costs will be driven by both scarcity of sites and various forms of legislation.

2.7 Legislation and Incentives for Recycling

Previous environmental legislation has focused upon the impacts of production and use of products. For instance, in the US the imposition of an excise tax on CFCs was intended to reduce the profit in producing these chemicals [Lee 1992]. However, the emphasis is now on the product EOL. Industry is going to be held increasingly more responsible for dealing with their EOL products. It is argued that the producer is rightly liable to bear the cost for the EOL products, because the producer has the most powerful weapon to deal with it, namely product design [Zussman et al. 1994].

Product take back legislation places responsibility on manufacturers for recovery and recycling of the products that they produce. In shifting the burden of waste management from local government to industry, manufacturers have direct incentives, in terms of financial impacts, to design products that are recyclable. The legislation is based on a desire to encourage activities such as extended product life, high levels of maintenance and repair, reuse of component parts and remanufacture. Basic recycling processes such as shredding are viewed as the last resort.

Germany has already established a programme that places responsibility on manufacturers to take back packaging from their products. The Electronic Waste Ordinance (EWO) drafted on October 15th 1992 decrees that retailers, distributors and manufacturers must take back used equipment, either for recycling or where recycling is not technically feasible, for safe disposal. Take back systems must be easily accessible to end-users and ensure a high level of returns. The cost of this operation will be included in the purchase price, to be paid by the customer. Virtually every item of electrical and electronic equipment comes under the EWO, from large items of office equipment such as computers to domestic appliances such as coffee makers and electric razors. The EWO recognises that the infrastructures and technology required to support extensive recycling cannot be established immediately. Therefore the EWO will be implemented on an incremental basis as viable recycling processes become available [Dillion 1994].

It is likely that the EWO legislation will result in 1.5 million tonnes of electronics product scrap in the "old" West Germany alone [Williams 1993]. For instance, Philips expect to receive 4 million Cathode Ray Tubes per year in the form of EOL TVs and computer monitors from Germany when the EWO is enacted [Clegg and Williams 1994]. In the case of products such as washing machines, Siemens estimates that product costs could increase by as much as 15% as a result of German legislation [Clegg 1992a; Kuhnel 1993]. Within the German market, all suppliers, both internal and external will have to meet the requirements of take back legislation to compete in that market. However, German producers may be at a disadvantage in the international market, unless other countries adopt identical legislation. The proposed German legislation was established to anticipate the international trend in environmental legislation which currently reflects emissions, health and safety at work and energy efficiency, but will also include products [Clegg and Williams 1994]. Initial moves suggest that it is likely that the EC (France and the Benelux countries already support the German legislation), USA and Japan will adopt legislation similar to that of the Germans [Clegg 1992b]. Dutch legislation on electronic take back is intended to be more stringent than that of Germany because it will encompass existing as well as future products. Dutch industry estimates that the collection and sorting of refrigerators alone will cost $35 per machine. For consumer electronics, Dutch industry estimates a rise in product price of 5 to 8 percent [Dillion 1994]. In Denmark, the effect of legislation is complicated by the fact that the country imports over 90% of its electronic products. France is also in the process of establishing similar legislation [Clegg and Williams 1994].

The mandatory take back of electronic products is a policy that has received particular attention by the US government and it is likely to be introduced as legislation by the US Congress in the near future [Chakrabarti 1994]. Currently several states in the USA prevent the landfill of used refrigerators, other domestic appliances (including computers) and batteries [Clegg and Williams 1994]. In Japan there is a recycling law, passed in 1991 that aims to encourage manufacturers to design products for recycling. It applies to domestic appliances, especially refrigerators, television sets, washing machines and air conditioning units [Clegg and Williams 1994]. As mentioned in section 2.6, Tokyo City Council has established procedures for the disposal of TV sets [Roy 1991].

The UK approach inevitably reflects the views of a Government that believes in the use of market forces and self regulation over centralised control. This is typified by the producer responsibility initiative, launched in 1993. Under this initiative the Government identified key industrial sectors such as motor vehicles, tyres, batteries and electronic equipment and requested that the associated producers devise plans that would result in the recovery of the maximum value from these products at EOL. If industry fails to undertake this task then the Government has issued the threat that more costly and onerous Government devised schemes will follow. Responsibility for devising plans for EOL electronic equipment is with ICER, the Industry Council for Electronic Equipment Recycling which was established in October 1992. It currently has 30 members, including material suppliers, waste management companies and several major equipment suppliers.

However, EC legislation is already making its impact in the UK with the Packaging Directive (Article 6 of the EC Directive 94/62/EC), which has to be adopted by individual member states. The directive obliges businesses that produce or use packaging to take responsibility for recovering and recycling packaging waste. The directive in the UK is being implemented under the provisions of the Environment Act 1995 and the Producer Responsibility Obligations (Packaging Waste) Regulations 1996. The details of the regulations were published on the 29th of January 1997, although the practical details still have to be finalised. Companies affected by the legislation have to prove that they are achieving the required level of recycling. They have a choice between complying individually, by registering with the Environment Agency or Scottish Environment Protection Agency, or by joining a collective scheme [Classe 1997].

Take back legislation is likely to be one of the most significant developments that has impacted upon industry. It is not an unreasonable assumption that many products being designed today will face legislation driven take back requirements in major European markets by the time they reach EOL [Bast 1994]. However, the extent of such legislation is uncertain. In an attempt to be proactive and avoid or mitigate against legislation, many companies have developed incentive schemes. The following sections provide case studies of such schemes.

2.8 Product Take-Back Case Studies

It is argued that impending legislation should be treated as an opportunity and not a threat. The idea of value added in manufacturing being reclaimed in the form of components and materials at EOL and used in the next generation of products is gaining in popularity. This section introduces such case studies in three main industry sectors: automotive, computer and electrical goods.

2.8.1 Automotive Industry

In Germany, BMW is involved with Ford, Mercedes, Opel and Porsche to address recycling issues. As Eberhard von Kuenheim, chairman of BMW stated, engineers will have to be concerned "not only with the construction, but with the destruction" and "to reduce the need to extract new raw materials from the earth and to reduce the amount of material which we dispose of" [Wolfe 1991].

In the UK, BMW have established a vehicle dismantling and recycling plant at Bolney in Sussex. The plant is capable of processing 2500 cars a year and BMW project that within five years all of the 16,000 BMW cars which are scrapped annually in the UK will pass through country wide plants similar to that at Bolney. The plant is run on procedures initiated at BMW's pilot project plant at Landshut in Germany. The plant purchases the car from the last owner for considerably more than a conventional car breaker. Depending on how many valuable parts that can be retrieved, a 10 year old car is purchased in the region of between £100-600. The parts retrieved are refurbished and sold "off the shelf" with a 90 day warranty. Since many cars become uneconomic to maintain when one expensive component fails on a car, the rest of the components are usually serviceable. The company envisages this operation as an opportunity to combine environmental responsibility with financial reward. The plant predicts that landfill costs will increase 40-fold over the next five years and therefore aims to minimise waste in all areas. Each car passes through stations on a disassembly line which strips the basic body shell, removing components such as entire engines and electrical ancillaries. With the body shell stripped of components its price in terms of pure scrap metal is £36 per tonne. Materials are sorted into 50 categories, separating complicated assemblies where possible. There are problems with items such as bonded metal, plastic and foam, for example the dashboard. However, the plant expects future BMW models to be more recyclable through feedback to the design process [Wolfe 1991].

In France, Peugeot has established a car recycling plant at Saint Pierre de Chandrieu, while in Japan, Nissan and Honda meet the requirements for component identification as laid down by the Automotive Manufacturers Association. In Italy, AFL Falck, a major energy and materials company estimate the economic opportunity to take back spent products is in the region of 14 billion dollars per year and is attempting to establish projects with Fiat, Mercedes, IBM and Zanussi [Williams 1993].

2.8.2 Computer Industry

Three leading computer manufactures in product take back are Hewlett Packard (HP), Digital Equipment Corporation (DEC) and ICL. They have all experienced economic benefits of product take back.

The objective of HP's Hardware Recycling Europe (HRE) Centre is to provide a cost-effective source of parts. Of the returns received in 1990, 60% were recycled, 35% landfilled and 5% incinerated. By 1992 65% were recycled, 5% landfilled and 30% incinerated [Clegg and Williams 1994]. Paton outlines some of the market characteristics of electronic equipment [Paton 1994]. Firstly, as product technology advances with each new product release, existing products are obsolete long before they are worn out. Secondly, prices for new products continue to decline rapidly despite significant improvements in features and performance. Thirdly, the rate of technological obsolescence creates strong incentives for customers to replace or upgrade their equipment frequently. Finally many customers have no convenient channel for reselling or disposing of obsolete equipment. In response, HP propose to produce a universal exterior product shell, while allowing board-level upgrades. The customer saves money by upgrading components instead of replacing the complete product. HP aim to handle a smaller volume of product, but higher component value.

DEC have undertaken a number of projects in the US and Europe to examine the benefits of recycling. At Nijmegen in Holland, DEC have established a European Materials Disposition Centre which is located next to DEC's major European repair centre. The centre collects spent electronic computer equipment from 40 collection sites in Germany, UK and France. The computer equipment is either repaired and resold; or dismantled into large high value sub-assemblies, such as motors that are used in current production; or are completely dismantled for material recycling. Feedback on problems incurred during product take back are provided to design engineers in order to improve future designs [Dillion 1994]. As a result of the high cost of landfill in Germany, the plant is profitable [Williams 1993].

ICL has established an Equipment and Returns Centre based in the UK at Byley in Cheshire. Each year the centre receives some 500 tonnes of used computer equipment encompassing everything from large mainframes, through workstations, to PCs. Approximately 20% by weight is refurbished and resold to customers, whilst 50% is reclaimed as spares to support products in the field. In 1993, annual revenues from refurbished systems and spares exceeded £5 million. The remaining 30% of products are sent to specialist contractors or to landfill. The contractors salvage any materials of commercial value using mechanical, electrical and chemical processes. Such materials include gold, copper and engineering plastics. A remaining 8% by weight is sent to landfill. One example of the revenue generated by refurbishment is the mainframe market, where companies, such as airlines who require the latest mainframe performance for customer response regularly purchase the next generation mainframe. ICL takes back the existing mainframe, replaces the cooling fans and subjects the system to software and hardware tests. The refurbished mainframe is then sold to organisations whose performance requirements are not so exacting.

For the future, ICL is concerned that the computer business is moving away from mainframes and towards workstations and personal computers. Mainframes typically date from a period where gold was liberally applied to printed circuit boards and edge connectors, in generous 5 micro metre layers. The move away has seen a reduction in the returns from recycling because workstations and PCs typically contain low value material, such as plastic, compared with high value metals in mainframes.

2.8.3 Electrical Goods Industry

Every year in Germany alone, at least 1.5 million tonnes of electrical and electronic scrap is produced [Fowler 1994]. Siemens, the world's sixth largest company has responded by establishing product recycling groups. The policy of the company is that landfill or incineration must be last resort options. This has led to the adoption of a number of design principles, including disassembly, which involves making products easy to take apart by using clips rather than screws. It has also promoted a reduction in the number of different materials used. Another division of the company, Siemens-Nixdorf already accepts its old computers for recycling, where parts such as the DC power supply are removed for re-conditioning.

A company which has introduced design for recycling is Rank Xerox of Germany. The principles of product reprocessing have been built into the component and product design. In Holland at Venray, the Company runs an asset recovery operation and a reverse manufacturing facility. This operation processed 50,000 field returned copiers in 1992 and 100,000 in 1993. In 1992, 755,000 components were reprocessed (51% by weight), 46% by weight were returned to their original material status and only 3% were sent for disposal [Clegg and Williams 1994]. The operation is integrated with the manufacturing facility, in order that reprocessed parts can be used in the production of new copiers. The design process aims to facilitate disassembly through the use of screws and clips instead of welds; and avoid materials with a multi compositional structure. The Rank Xerox policy of leasing products ensures its reprocessing facility a supply of spent copiers and allows long term planning and investment. The Xerox 5052 copier has a 25% reprocessed part content and this is anticipated to rise to 75% depending on the availability of the X1050 model copier and other predecessor carcasses [Williams 1993].

Keymood Ltd were established by Rank Xerox UK, to take back their equipment. Each year Keymood receive approximately 40,000 machines, of which 17,000 are completely refurbished and sent back to Rank Xerox for leasing to customers. The remaining 23,000 are dismantled and processed for spares which are used in the refurbishment business or are recycled. The long life of the copiers, which is in the region of 40 million copies, strengthens the argument for refurbishment. This is demonstrated by the fact that only 5% of copiers received by Keymood are not operational. To make sure copiers and used components are returned, manuals set out agreed credits for customers and engineers for components returned during service or copiers at contract change.

2.9 Third Party Relationships

Some organisations are moving towards collaboration with third party recycling companies. One such company is The Bird Group, which has 25 sites across the UK. They have established close links with the Rover Group to set up a standard strategy for vehicle recycling. The Rover Group allow members from the Bird Group to take part in the design process to increase the ease of disassembly and the yield of recyclable materials [Rover/Bird Group 1993].

For a number of years BT has operated a recycling scheme for rental telephones. The collection costs are minimal, as the scheme uses return journeys of BT equipment supply vehicles. A third party recycler, Mayer Cohen recycles approximately 3.5 million BT telephones per year, with the profits of the operation shared by both companies. They have discovered that there is less value to be recovered from the latest design of telephones. The percentage of plastic is increasing whilst the percentage of precious metals and non-ferrous metals is decreasing. The telephones taken back have changed from 65% electro-mechanical to 60% electronic content. The latest generation are difficult to take apart, have more surface mount chips and now use carbon tracks on the PCBs instead of plated gold contacts. The design life of a telephone is on average 18 years, where in practice it is replaced after 18 months. Therefore 80% of the telephones Mayer Cohen take back are operational. For this reason a large number of products and components are reused for example, 16-20,000 phones per month sold to Poland. This example demonstrates that where products still have a functional life at an EOL dictated by UK consumer tastes, then it may be economically and environmentally conscious to export such products to emerging countries for further use. In many such emerging countries scarcity and hence cost of landfill is not a problem, however such a policy may be environmentally damaging.

In 1993, Mayer Cohen established a remanufacturing facility dedicated to answerphones. As a result, three types of remanufactured products were introduced in May 1994 for use as replacements during the maintenance of rental equipment [McAloone 1993].

Trimphones provide an example of the economic liability caused by products designed without consideration to the end of life cycle. Tritium gas contained in the dials on Trimphone telephones produces a luminescent glow allowing the dials to be seen in the dark. Currently there is no safe disposal route for such materials and hence Trimphones withdrawn from service are separated and held in a licensed storage facility. Final costs to BT for the storage and disposal of this waste are likely to be £10 million by the year 2000 [BT 1994].

2.10 Conclusion on Product Take Back

The above case studies demonstrate that a number of companies in the automotive, computer and electrical goods industries already have product take back schemes which are highly successful, despite an historic lack of input at the design stage. Manufacturers are either collecting and recycling the product themselves, or paying a third party recycler to undertake the operation. In some cases, a take back operation may be hampered by a lack of supply of EOL products. One method of ensuring product take back is through product leasing. Industries such as photocopying are already presented with incentives to design products to maximise product utilisation and hence profit over many life times, rather than simply focusing on the volume of initial sales and manufacturing costs [Stahel and Giarini 1991].

toner cartridges are returned via United Parcel Services at a cost to Xerox of $4 per cartridge. The disassembly cost for the previous model was between $10 and $15, which meant that the operation was barely profitable. However, due largely to design changes and also an increase in the volume of returned cartridges, the operation has become profitable. It now costs $60 to manufacture a new cartridge compared with just $35 to remanufacture a returned cartridge [Clegg and Williams 1994].

In the late 1980's a number of companies reported dramatic cost and time savings in new product development through the establishment of multi-disciplinary design teams. This integration of the marketing, manufacturing and support functions was known as Concurrent or Simultaneous Engineering (CE/SE). Instead of designers developing a concept in isolation and then passing it "over the wall" to production engineers, design concepts were evolved continuously through team based communication. This multi-functional approach expedites product development from stage to stage. Not only has CE produced cost and time savings, it has also produced product life cycles of superior performance and quality [Brophy 1994].

2.11.1 Concurrent Engineering

CE is defined by the US Institute of Defense Analysis [IDA 1988] as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. Its aim is to ensure that designers from the outset, consider all elements of the product life cycle from conception through to disposal, including quality, cost, schedule, and user requirements" (see Appendix A).

CE can be categorised into three areas, teams, tools and techniques. In its broadest definition CE is defined as the consideration of all design "trade off" by a multi-disciplinary team at the earliest stages of design, with the help of "right first time" tools and techniques to aid decision support [Evans 1991]. The team consists of designers and individuals from all other related functional areas of the product design. The team members can therefore contribute to the "right first time" design of product and processes by early identification of potential problems and timely initiation of actions to avoid costly rework [Pennell and Winner 1989].

There have been many implementations and much research work on design methodologies for a number of perspectives within the life cycle of a product. They typically involve collecting data from many sources - say the outline design, tool design and production methods - and presenting the results in a format whereby the impact of a design decision can be made by a multi-disciplinary design team. The aim is to find opportunities to improve the design. They provide two types of advice to designers, qualitative and quantitative. Qualitative advice is in the form of general rules on the specific domain, while quantitative advice is in the form of scoring and cost systems into which designers provide the input [Rose 1993]. The more widely used methodologies are those which provide quantitative advice and thereby encourage designers to seek alternative and improved design solutions [Leaney 1992; Miles and Swift 1992; Ekman 1992; Lewis 1992; Boothroyd 1992; Vance 1992; D'Cruz 1992; Atiyeh 1992; Andreasen et al. 1992]. These have included Design For Manufacture (DFM), Design For Assembly (DFA), Design For Serviceability (DFS) and Design For Disassembly (DFDA). DFM and DFA techniques have proven case studies which demonstrate reduced costs through the increased manufacturability and assemblability of products [Brophy 1994; Leaney 1992]. The automotive company Ford have reported total savings in excess of $1 billion through the widespread application of DFM/A software [Winner et al. 1988]. In the disassembly domain there has been the development of methodologies for integrated assembly and disassembly sequence generation and evaluation [Fogg and Simon 1992; Dewhurst 1992; Laperiere and ElMaraghy 1992].

A Design For Recyclability tool has been the aim of several research initiatives. The work has concentrated on the necessity of supporting the designer with quantitative information concerning process options for product EOL [Navin-Chandra 1991; Wallace and Suh 1993]. This support is in the form of software which assists the designer in identifying compatible recycling design solutions.

In the product take back domain the more proactive organisations, typified by BMW, have begun analysing product designs to improve the amount of recycled material used in the construction of the car and also to improve the dismantling and recycling of materials at the end of the cars life. This analysis currently relies exclusively on experienced designers and engineers reviewing designs and proposing changes. The company has also produced some generic guidelines that make disassembly simpler. These comprise of obvious qualitative information, such that glue and rivets are undesirable for disassembly. Conversely, DFA and DFM methodologies recommend the use of such assembly technology.

This section has demonstrated the importance of product design in determining the life cycle profitability. It has introduced the concept of CE and the use of tools in the form of quantitative and qualitative methodologies that support the design of various life cycle perspectives. However, it appears that there is no single methodology that provides decision support to the design process on the whole product life cycle.

2.12 Conclusion

This chapter has demonstrated the need for the research. It has shown that recycling is important and that legislation is increasing its importance and making it non optional for companies. The research has shown that the domestic white goods industry has little experience of product take back at EOL, leaving it one of the least prepared to deal with the demands of new take back legislation. Such legislation has the potential to bring serious financial strain upon a company, however there are many case studies which demonstrate that product take back and recycling is economically sound. Design is a key element in ensuring that a product is economically viable to take back and recycle. By its nature, design is a complex process of decision making.

The chapter has shown the importance of product design in determining the life cycle profitability. It has introduced the concept of CE and the use of tools in the form of methodologies that support the design of various life cycle perspectives. However, no single design methodology was found that provides the design team with decision support on the design of the whole product life cycle. Hence, there is a need for such a decision support methodology to support the design process. Such a methodology must influence the design of product life cycles to produce economically superior products.

3. Literature Review

The aim of this chapter is to provide a review of current work in both academia and industry, with regard to the development of methodologies that consider life cycle design. Hence, the first sub-objective of the research, to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products is partly met through the second sub-objective of undertaking a literature and industrial review.

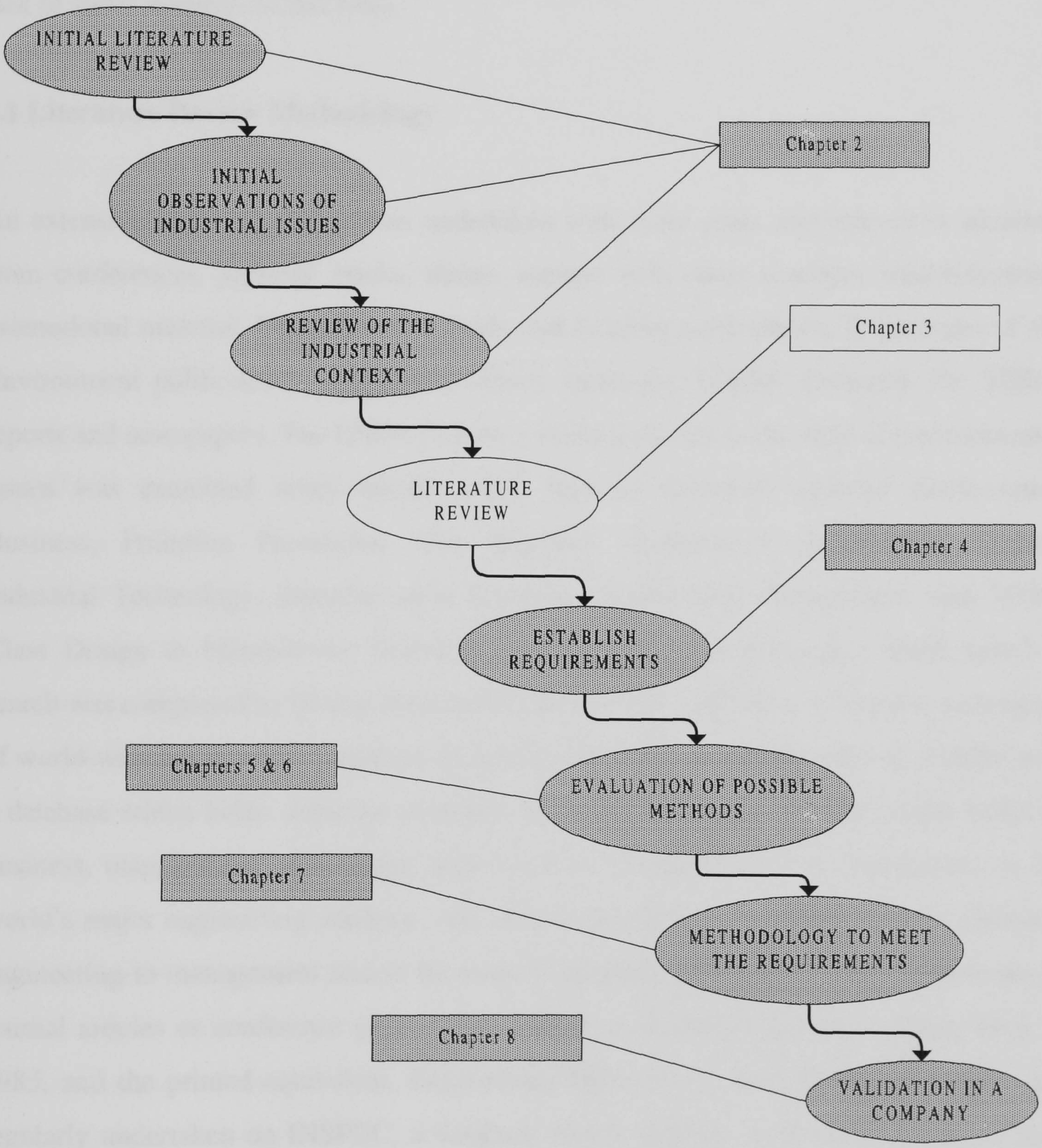

Figure 3.1: Relationship of chapter with research methodology

The chapter reviews work in the separate fields of Life Cycle Analysis (LCA) and Life Cycle Costing (LCC). It is shown that there are a lack of practical methodologies despite the demonstrated need for decision support with regard to the economic consequences of life cycle design. A lack of work in dealing with the type of uncertainty associated with the product life cycle is noted and a review of ways of dealing with uncertainty undertaken.

The chapter demonstrates the novel nature of the research by showing the need for and lack of methodologies in this field.

3.1 Literature Review Methodology

An extensive literature survey was undertaken over three years and references obtained from conferences, journals, books, theses, contact with other academic establishments, promotional material, Department of Trade and Industry publications, Department of the Environment publications, magazines, library databases, EPSRC (formerly the SERC) reports and newspapers. The ENDS Report, a leading journal in the field of environmental issues was examined every month. Other journals surveyed included Environment Business, Pollution Prevention, The Engineer, Professional Engineering, Eureka, Industrial Technology, Manufacturing Engineer, Engineering Management, and World Class Design to Manufacture (formerly Manufacturing Breakthrough). Each month a search was completed by Dialog Information Services of California, USA on a wide range of world-wide information databases. In addition searches were performed on ABI/Inform, a database which holds abstracts of articles from 800 academic journals in the fields of business, management, and related areas; and on Compendex Plus. Compendex is the world's major engineering database, and covers all aspects of the subject from chemical engineering to management issues. Its focus is academic and most of the abstracts are of journal articles or conference papers. The Library at Cranfield has discs dating back to 1985, and the printed equivalent, Engineering Index from 1960. Further searches were regularly undertaken on INSPEC, a database which contains world-wide abstracts from approximately 4200 journals, conference proceedings, books, reports and dissertations.

The coverage includes all aspects of physics, electrical engineering, electronics, computing and information technology and computers in manufacturing.

3.2 Life Cycle Design

Life Cycle Design is defined as the consideration of the product design for all stages of the life cycle from raw material acquisition, material production, product manufacturing, distribution, usage, disposal, recycling through to reuse [Alting 1993; Alting and Jorgensen 1993; Keoleian 1994]. The holistic life cycle is viewed as having five life cycle phases; a pre-production raw material extraction phase; a component and product production phase; a distribution phase; a use phase and a disposal/recycling phase [Legarth et al. 1994; Lal Tummala et al. 1994].

The design of a product strongly influences the economic and environmental performance of the product throughout all stages of the product life [Wenzel et al. 1994]. Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) are methodologies that have been found to be valuable in evaluating and providing decision support on the implications of life cycle design concepts [Keoleian et al. 1994].

3.2.1 Life Cycle Analysis - LCA

This section describes LCA. It shows that LCA is a useful tool in assessing the environmental costs of product and process design. However, it demonstrates that there is a lack of development in LCA methodologies to consider the economic impacts of product design.

LCA is defined as a class of techniques which attempt to identify systematically all the environmental implications associated with a product or, more generally, any human activity. It was originally developed as a tool for commercial decision making, but has been adopted to influence design by encouraging designers to question issues [Clegg and Williams 1994; Wenzel et al. 1994; Ayres 1993]. Consider the example of selecting the use of either fluorescent or incandescent light bulbs in the design of a new office complex.

The use of compact fluorescent bulbs in place of incandescent light bulbs can result in substantial energy savings. Over a 10,000 hour period, an 18 watt fluorescent bulb in comparison to a 75 watt incandescent bulb results in energy savings of 570 kilowatt hours. This translates, assuming coal fired power generation to 500 pounds less of coal and therefore 1,600 pounds less of carbon dioxide emissions. However, fluorescent bulbs contain up to 5 mg of mercury [US-OTA 1992]. Such "trade off" highlights the need for analytical tools, such as LCA, to examine the environmental benefits of alternative design choices [Hocking 1991; Van Eijk et al. 1992].

Fundamentally, LCA consists of four stages, goal definition, inventory analysis, impact assessment and improvement plans or valuation [Snowdon 1994]. The first stage, goal definition and scoping is a critical component of LCA, because it provides a reference for the whole LCA analysis and helps define the boundaries, assumptions and limitations of a particular LCA [Warren et al. 1994]. The second stage, inventory analysis involves a quantitative measure of the inputs such as raw materials or energy; and the outputs such as air, water or solid emissions, throughout the life cycle of the product. However, it is also necessary to know how the quantities should be weighted to reflect their relative health and environmental risks. For example, how should a kilogram of sulphur dioxide emitted to the air during manufacture be compared with a kilogram of solid waste going to a landfill. Therefore impact assessment, the third stage, involves making judgements on the relative importance of the findings, such as the effect on the ozone layer from substances released or the contribution to global warming made by the quantity of CO_2, NO_x etc. released. Finally improvement targets for the future are established to progressively reduce environmental impacts [Snowdon 1994; Tipnis 1993; Cohan and Gess 1994, Fava and Weston 1994; Warren and Weitz 1994; Besnainou and Coulon 1994; Fava 1991; Fava 1993; Graedel 1994].

LCA has been used for more than 20 years in a wide variety of organisations for many different reasons [Warren and Weitz 1994; Tipnis 1993]. For instance, LCA analysis has been used by the EU to decide whether or not a product should be awarded an ecolabel. Such a label conveys to consumers information on the relative "environmental friendliness" of products [SERC 1993]. A recent survey has shown that LCA has been most widely implemented in industries where there is a strong consumer orientation, such as the automotive and packaging industries and to a lesser extent in the appliance and electronic industries [Clegg and Williams 1994; Sullivan 1991].

LCA does not account for other, non-environmental aspects of product quality and cost. A joint ESRC/SERC/AFRC workshop in 1992 identified that the existing focus of LCA on emissions and natural resource use provides little useful information on the economics of environmental impacts [SERC 1993; SETAC 1991; SETAC 1992; SETAC 1993; Wall Street Journal 1991].

3.2.2 Life Cycle Costing - LCC

LCC has been used for many years in the areas of building design and military applications in order to reduce future operational and maintenance costs to the operator and the manufacturer [Dale 1993; Dhillion 1989; Koyama 1993; Flanaghan et al. 1989; Gustafsson 1993; Robinson 1993; McGeorge 1993; Ashwoth 1993; Bull 1993; Sheldon and Osmond 1994]. In these two industries attempts are made to forecast the consequences of decisions before proceeding despite the heavy odds against a forecast being correct. If all members associated with the product design are involved at the forecasting stage, then it is possible that the ultimate psychological goal, that of confidence, which is often a prerequisite to design decisions, may be achieved. If the outcome of the result does not materialise as predicted, then at least it can be shown that the decision was based on knowledge and not chance.

LCC is defined as the sum of all costs incurred by a product over its entire life, currently and in the future using present value techniques [Dhillion 1989; Mott 1987; Larsen 1994; Bush 1993]. A more detailed definition is provided as all internal and external costs associated with a product, process, project or activity throughout its entire life cycle - including research, design, development, raw materials acquisition, production, testing, packaging, supply and delivery, after sales service and warranties, modifications and upgrades, product retirement and recycling/final disposal of waste materials [Warren and Weitz 1994; Bently 1990; Blanchard 1978]. Both costs to the customer and the manufacturer are considered, because ultimately a high operational or running cost will result in dissatisfied customers.

LCC is applied in an attempt to decide how much should be invested now in order to reduce costs in the long term. In a similar manner, product designers faced with product take back have the same dilemma. How much should they invest now in the product, in terms of manufacturing cost to reap the possible rewards at EOL [Dale 1993].

In the UK, costing models have been developed independently by the controllerates which deal with sea and air defence systems. There are two main reasons [Kinch 1993] why life cycle costing is appropriate for the business of defence procurement and operation. The first is the amount of capital at stake compared with the past. For instance, the unit price of a World War II Spitfire was £3,000, whereas the current cost of a Tornado is in excess of £10m and a Westland EH101 anti-submarine helicopter £24m. The second reason is the length of time a weapon system may be expected to remain in service. In the 1940s and 1950s a new type of aircraft was introduced on average every three years. Currently it is normal for military products to last 25 years. Examples include the RAF's Canberra which has been in use since the 1950's; the Buccaneer which flew in 1958 and was used actively during the 1991 Gulf War; and the Westland Sea King which has been in service since the 1970s and is expected to remain so well past 2000. Therefore the costs of specification, development, purchase, operation, support and disposal must all be part of the initial design process.

Whilst the use of LCC in the defence industry is common, its application in the commercial world is less evident. A survey by Coventry University of nine companies showed that while all were able to estimate their product manufacturing costs, only three companies had attempted to define post sale costs. Further case studies have shown that the purchase cost of a product typically represents between 20-40% of the product's whole life cost [Osmond, et al. 1994]. Experience in the US defence industry has shown that 70% of the total cost of a product will have been committed before the production stage is reached [Kinch 1993]. Service and disposal costs have the potential to accrue over the product life time to exceed the original purchase cost. By ignoring such costs and concentrating on solely manufacturing costs, companies may expose themselves to long term risk, especially with the advent of product take back legislation. Products designed in this manner not only risk gaining a poor environmental image, but also tend to attain a low consumer image with poor reliability and high service costs This is analogous to the problems currently associated with the decommissioning of nuclear power plants, a process which was not fully understood or considered during design.

3.2.3 Conclusion

LCC and LCA share the same life cycle perspective. In practice, LCA has addressed broad environmental impacts, but has had few applications to real business decisions [Clegg and Williams 1994]. LCC has been used by the military and construction industries for a number of years. However, LCC has seldom included environmental legislative, disposal or product take back costs [Fabrycky and Blanchard 1991; Dhillion 1989; Henn 1993; Fiksel and Wapman 1994]. There is the need for a methodology that provides advice on product designs which are economically sound to operate, dispose and recycle [Keys 1990; Tipnis 1993]. It is advocated that such economic analysis should deal with the uncertainty of future values and events [Tipnis 1993; Warren and Weitz 1994; Larsen 1994; Dhillion 1989]. Therefore a major challenge to a new methodology will be its ability to deal with changing economics, for instance, predictions of the impact of new technology or legislation, in order to ensure that future costs are not understated in design [Clegg and Williams 1994; US-EPA 1993].

3.3 Life Cycle Costing and Uncertainty

The aspect of uncertainty within LCC has in the past been generally dealt with by ad-hoc sensitivity analysis. Coogan argues that sensitivity analysis is a critical step in the process of LCC to mitigate uncertainty [Coogan 1993]. It is used to determine the impact of changes in parameters. In the defence industry, a LCC model is developed and sensitivity analysis performed by varying each parameter independently and recording the results.

An LCC methodology applied to the design of future products must by implication be an estimate as anything that occurs in the future is certain [Larsen 1994; Sheldon et al. 1990; Perks et al. 1993]. Therefore all costs are considered uncertain, however the uncertainty of service costs will be greater than those of manufacture because they are further into the future, and in the same vein, the uncertainty of recycling costs will be that much greater than those of service costs. It is identified that there is a need for new LCC methodologies, that examine the economics of product design with product take back and the associated uncertainty [Fiksel 1993; Henn 1993].

Hence uncertainty has a major influence on LCC, especially where product life cycles may last 20 years or more.

3.4 Causes of Life Cycle Uncertainty

Consumer behaviour will change, not just at the point of purchase but through use and into disposal. May be all waste will be separated by the consumer and collected in categories. Certainly the infrastructure for waste management, already moving from a cottage industry towards recycling factories will change. The value of today's components and raw materials will change, with new markets opening up and old ones disappearing. Labour costs will change and the technology used for waste management will change dramatically. May be robots will be able to disassemble damaged cars? May be the value of recycled plastic will treble? or halve? [Fowler 1994; Zust 1993]

In manufacturing, the product volumes are known with some degree of certainty making the selection and cost of the manufacturing process relatively easy to justify at the design stage [Thurston and Liu 1991]. However, with product take back, the volumes returned are uncertain and therefore the justification of the remanufacture processes is difficult. For example, the electronics industry, including companies such as Philips, Hewlett Packard, ICL, AT&T and Xerox, are of the opinion that while automated disassembly is technically feasible, it is only suited to high volume standardised parts. For example, the IPA at Stuttgart has developed an automated robot disassembly cell for EOL telephones, which has been successfully implemented by Deutsche Bundespost Telekom in its remanufacturing facility [Clegg and Williams 1994]. However, most organisations that take back EOL products view manual disassembly, using appropriate mechanical aids, as the most current practical approach. Mirec, a Philips electronic product disassembly operation, have found it difficult to justify automated disassembly because the EOL products they take back are of an indeterminate type, volume and quality [Clegg and Williams 1994]. If this uncertainty could be reduced through customer schemes (perhaps linked to product tracking systems) that reward for the return of EOL products, then the case for automated disassembly could be justified.

One of the important issues in product take back is the cost and ability to retrieve the EOL product. In the simplest case for those companies who are vertically integrated into distribution and sales, the collection and return cost is simply the reverse of the distribution cost. In some cases the cost may be less because many return routes are not utilised. Companies such as Digital, Hewlett Packard and ICL who take back their own products reduce the size of the used market and have a direct sales lead to a potential customer. However, some organisations fear their logistics costs may rise by a factor of 20. Such an increase may be passed on to the consumer, but at the risk of reduced sales volume [Clegg and Williams 1994].

Over the next 20 years the legislation dealing with products, their environmental impact and their EOL treatment will change. This section has shown that there are many causes of uncertainty throughout the product life cycle. Dependant on their occurrence in the life cycle, some causes of uncertainty are more uncertain than others. In this scenario it is understandable for the designer to ignore the possible changes - they cannot predict the future exactly and so cannot be expected to deal with it. Uncertainty at this level is not typically an influence on design today, but a longer term consideration of environmental impacts. The future economic well-being of a company may well depend on design decisions made a decade previously; so we can expect the language of uncertainty to become more common as designers seek ways to cope with this challenge [Dewhurst 1993].

3.5 Uncertainty and Risk

A common method of dealing with uncertainty is through the application of risk analysis. The aim of this section is to examine the relationship of uncertainty with risk analysis, to demonstrate that existing risk analysis is not without its problems and that ideally a designer should try to opt for a robust economic product strategy in the face of uncertainty.

The earliest distinction between uncertainty and risk was made by Knight in 1921, who stated that risk was related to planning situations where probabilities of outcomes were known or could be allocated [Knight 1921; Webb 1996]. This work was further developed by Spencer in 1962, which resulted in a series of investigations into both the nature of risk and uncertainty and their application in industry. Spencer concluded that in the absence of uncertainty, the role of management would be superfluous in all but the initial phases of a project [Spencer 1962]. In the 1960's operational research activities turned their attention towards the problems of uncertainty in the planning process [Gupta and Rosenhead 1968]. Such activities were concerned with problems associated with investment planning, based on the concept that optimality may not be the only criterion for project selection, with the emphasis shifting towards robustness [Hillier 1963; Hertz 1964; Best et al. 1986]. As a result, the subject became dominated by statisticians and operations research practitioners, resulting in complex models that were based upon probability distributions [O'Donnell and Rhodes 1983; Webb 1996]. Hence, risk analysis can be identified as being distinct from uncertainty by the existence or application of a probability distribution within which to analyse the possibility of any one event occurring statistically. Therefore elements of uncertainty have been converted into elements of risk through the allocation of a probability distribution. Such a probability distribution can either be objective through an empirically based result, or subjective through canvassing experts for their opinions on the future [Jeffery and Greaves 1991]. Risk therefore becomes objectively measurable and uncertainty something that is perceptual in nature and human centred. The reason for this shift from uncertainty to quantifiable risk was largely due to the fact that decision makers prefer to be informed about the future in a form which lent itself to a quantifiable selection process [Levy and Sarnat 1986].

Thurston and Liu have used a form of risk analysis, known as probabilistic utility analysis to determine the effect of uncertainty in estimates of performance on the ultimate desirability and ranking of product design concepts [Thurston and Liu 1991; Thurston and Blair 1993; Thurston and Essington 1993]. Utility analysis has its origins in the late 1940's [Thurston 1991]. The application of the technique requires a designer to allocate weightings and probabilities to design attributes. For example, consider the problem of an individual component for a commercial aircraft. The current design is considered to be too heavy but is relatively inexpensive. Under the uncertainty of rising fuel costs the designer could think that weight reduction in order to increase fuel efficiency is more important than manufacturing cost. In this case the designer has to assign weightings, say of 60% to weight and 40% to cost; and the maximum cost the designer is willing to pay to achieve a 1 kg weight reduction is determined from a series of questions and answers. In just this simple example the mathematics required is large and in addition linear assumptions of the methodology are required because a designer will be less willing to pay to achieve weight reduction as weight decreases.

In general, utility theory attempts to automate the decision making process rather than providing the design team with practical decision support. The human as an information processor is good at making trade off decisions, however it is weak in processing large amounts of data calculations [Matin 1994; Flanagan et al. 1989]. Whilst mathematically correct, utility theory goes against current evidence on the success of Concurrent Engineering design teams [Smith and Reinertsen 1991; Duffy et al. 1993]. Methods which incorporate uncertainty through statistical techniques have resulted in output which is oversimplified and deficient to decision makers [Jeffery and Greaves 1991]. British Aerospace Dynamics use risk analysis in their project management cost estimating function and have found that the hazard of projections is not that they will be wrong, but that they will be accepted literally and that an illusion of knowledge will develop. Therefore probability is represented as simple triangular distributions [BAe 1991]. This pragmatic approach avoids the excessive complexity in the working practice of probability distributions. In a review of risk quantification of tactics associated with parallel tasks in Concurrent Engineering, Matin categorises the risk as being one that is high, medium or low (a triangular distribution) [Matin 1994]. This approach is supported by other researchers, who recognise that time and resource constraints often mitigate against an exhaustive quantification exercise being undertaken [Ireland and Shirley 1986].

3.6 Robustness

An alternative approach to risk analysis is the application of robust design principles. Such techniques are an accepted method of dealing with uncertainty in manufacturing. This is typified by the use of the Taguchi strategy to product and process design [Bryne and Taguchi 1987]. Snee states that a "process output or product is robust if its performance is insensitive to uncontrollable variations in conditions of manufacture, distribution, use and disposal" [Snee 1993]. Therefore a robust product or process is more likely to perform as expected because problems have been anticipated and preventative measures taken, therefore the degree of uncertainty has been reduced.

Benjamin and Mayer have applied Taguchi type experiments to the design of manufacturing systems. A manufacturing system traditionally has many monitoring procedures to measure and report key performance indicators such as machine utilisation, scrap rate, throughput rates, inventory levels. Benjamin and Mayer note that there is considerable effort in the operations monitoring, and propose that manufacturing systems should be robust, rather than require control mechanisms to monitor and deal with disturbances. They propose a methodology which is based upon a computer model and the application of Taguchi methods to achieve system settings so that the manufacturing system is robust to external disturbances [Benjamin and Mayer 1992].

If an analytical model of a system can be defined, then it is possible to apply linear analysis to predict the performance of such a model and identify which variables provide the greatest contribution to variability. Action can then be taken against those variables to ensure that a system is robust. References to the sensitivity of capital recovery to changes in the variables defining it refer to the use of differential calculus to deal with uncertainty [Morris 1960]. Brown expanded on the work of Morris and that of non-linear control theory to develop a method using quasi-linearisation which provides an analytic sensitivity analysis that is rigorous compared with the traditional ad-hoc sensitivity analysis [Brown 1968].

Planning for the future constitutes an acceptance that events may not occur as planned, and that assumptions or forecasts may be wrong. To improve the chances of successfully meeting the future, it is useful to adopt methods which will ensure that in the planning or designing of products, they will be successful over a range of conditions, in other words they will be robust.

3.7 Chapter Conclusion

This chapter has provided a review of current work in both academia and industry, with regard to the development of design decision support methodologies that consider the design of the product life cycle. Hence, the first sub-objective of the research, to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products has been partly met through the second sub-objective of undertaking a literature and industrial review.

The chapter reviewed LCA and LCC. Despite the current use of LCA and LCC, their application does not meet the requirements of a methodology to provide decision support on the life cycle design of products. A new methodology will have to deal with the effects of uncertainty of predicting future events and costs. The type of uncertainty associated with the product life cycle was discussed and a review of existing ways of dealing with uncertainty was undertaken.

Despite the obvious industrial need, demonstrated here and in chapter 2, for a new methodology it is shown that there is currently a lack of methodologies that deal with the design of the product life cycle and its associated uncertainty.

4. Requirements of a New Methodology

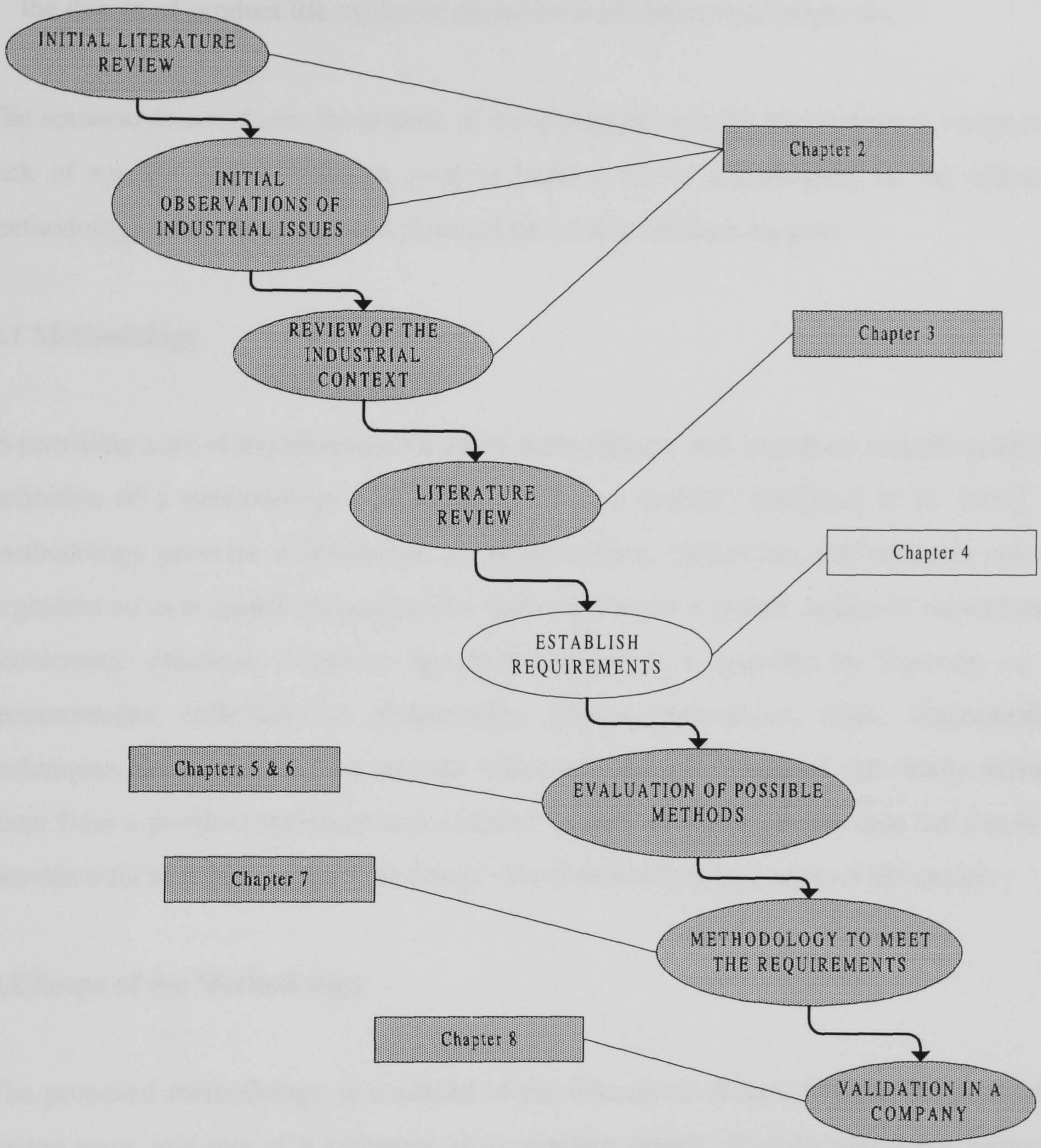

Figure 4.1: Relationship of chapter with research methodology

This chapter describes the process of designing a product with regard to its life cycle costs via a life cycle design scenario of two simplified chair concepts, one more recyclable than the other. The use of such a scenario, despite being simplified, identifies the requirements and unique characteristics of a design decision support methodology by demonstrating the types of decisions involved. This meets the first sub-objective of the research to:

- to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products.

The scenario demonstrates those parts of the design process for which there is currently a lack of support and is therefore used to build a set of requirements for an effective methodology, one which provides practical and usable decision support.

4.1 Methodology

In providing a set of requirements for a new methodology, it is important to understand the definition of a methodology. "Methodology is not method" [Marshall et al. 1987]. A methodology provides a framework in which models, techniques and concepts can be organised so as to enable its prospective users to achieve a greater degree of control over problematic situations. Hence an appropriate definition is provided by Yeomans as, "a recommended collection of philosophies, phases, procedures, rules, diagramming techniques, documentation and controls which will allow a structured and clearly defined route from a problem statement to a solution" [Yeomans 1984]. In this case the aim is to provide information to support the design of economically robust product life cycles.

4.2 Scope of the Methodology

The proposed methodology is confined to the domain of design. One of the aims of a design team, and that of a company, is to generate design solutions which are balanced acceptably between environmental and economic performance in order to satisfy a market opportunity and/or to take a long term financial perspective. Other metrics such as quality and time to market, which also contribute to the acceptance or otherwise of the product in the market place are taken into account through their ultimate effect on the economics of a product range. A poor product performance in relation to customer requirements will lead to low sales figures or an increase in warranty payments. Therefore such success factors should be taken into account in an economic model. For example, as stated in the popular press, Lancia no longer sells cars in the UK, a fact which is largely attributable to poor sales figures which in turn were a result of the corrosion problems associated with their cars in the 1970's and not the cars they produced in the 1990's.

4.3 The Scenario

Already initiatives have been undertaken in Holland to examine the environmental qualities of chair design. A chair is an uncomplicated design, which facilitates understanding of the design process with regard to environmental issues. Hence, the scenario is based upon the design of a chair. The Dutch study is introduced, followed by the design scenario generated from the research, which demonstrates the requirements of a new methodology.

4.3.1 The Environmental Perspective

Ahrend are a Dutch manufacturer of office chairs. As part of a collaborative initiative between the TNO Product Centre at the University of Delft, the Dutch Government and Ahrend, an environmentally conscious chair design was commissioned. An environmental expert and a design consultant were allocated to the company to work alongside the in-house design departments, with the brief to bring an environmental improvement to a new range of office chairs currently under design. The team identified one area of concern with the current design based mainly on the use of composite materials which would be difficult to recycle. They identified that this is of concern because product take back legislation is looming in Europe and as a result the team redesigned the chair. The existing method of manufacture for seat covers comprised of layers of polyurethane foam, textile and polypropylene welded inseparably together. In the new design the seat cover was attached with a draw string, which when cut allows the materials to be separated quickly and cheaply. Other design changes included the elimination of heavy metals in the plastic pigments and changing the base from polypropylene coated steel to glass-fibre reinforced nylon. Additionally the suppliers of the gas piston and castors agreed to take back their components from the EOL chairs. Overall such changes resulted in a 50% reduction in energy use, with emissions from substances such as carbon dioxide, phenols and fluorine reduced by between 40-80% [Webb 1994].

This analysis which led to the redesign of the chair was not driven by the economic life cycle implications of the design, nor did it include analysis of uncertainty, however a manufacturing cost reduction of 45% was claimed. The following scenario demonstrates that such an omission could lead to long term financial liability. In order to make design decisions that ensure financial viability it is essential to consider all life cycle costs that may be incurred and the associated uncertainty.

PART	MATERIAL	ENVIRONMENTAL CONCERNS
Castors	Nylon	high energy content, difficult to recycle
	GR-steel core	difficult to recycle and disassemble
Base	Nylon	high energy content, difficult to recycle
	Pigments	possible heavy metals
	Chrome	emissions during manufacture
Seat/back	ABS/wood/steel	emissions, material separation
	Polyurethane foam	emissions, material separation
	Nylon or Polyester	emissions, material separation
Armrests	Nylon	materials separation
	Steel	materials separation

Table 4.1: Areas of concern in the environmental analysis of the original chair design

4.3.2 The Economic Perspective

The following simplified scenario is based on the chair example generated from the research, but in this case the life cycle economics and uncertainty elements are highlighted instead of the environmental analysis that was conducted by TNO. The chair design used is a basic example without armrests, castors or cushions. The aim of the design is for a functional low cost chair and for the purposes of the scenario two initial design concepts are identified, one which has short term financial benefits, the other with longer term benefits, see Table 4.2.

In the first case, the chair is produced from GRP, glue, a number of brackets and steel screws. The initial cost to manufacture the chair is low at £20, partly due to the low cost of GRP at £1,500 per tonne [Ashby and Jones 1986] and the lack of tooling required in manufacture. However, the lack of material still useful at EOL means that few economic gains can be achieved later in the life cycle. In the short term, the first case would appear to be attractive. If the company was to take back the product at the end of the life cycle it would cost £8 in recovery, £1 more than the second case because little thought has been given on the ability to stack the chairs and so make storage and transportation easier. In addition, because glue was used in the assembly process to improve the efficiency of securing the base, then disassembly is difficult and costs £3 more than the second case. The only valuable items recovered are the 4 brackets of the base which at a £2 scrap value have little worth. A landfill cost of £1 per chair is incurred to dispose of the GRP. The result is that the overall cost of recovering the product is £9 (£2-£(8+4+1)) to the company. In addition, it is assumed that sales are only 4,100 per year and that 80% of these chairs are returned. Hence, the long term profitability of taking back the chair would be £11,480 (£10*4,100+£-9*3,280) per year. Such analysis demonstrates the need of an economic life representation that allows the manipulation of variables to facilitate multi-disciplinary debate. The profitability of not taking back the chair at EOL would be £41,000 (£10*4,100). Given this situation, a company would not take back the chair at EOL unless legislation deemed it mandatory.

	GRP Chair	£	Plastic/Steel Chair	£
1. Sales Price		30		30
2. Manufactured Cost				
Material Cost	4 legs/back/seat/glue/ 4 brackets/12 screws	-10	plastic/bracket/steel base/ 4 screws	-20
Manufacture/ Assembly/ Logistics Cost	Fabrication and manual assembly	-10	Injection mould and manual assembly	-3
TOTAL Manufactured Cost		-20		-23
3. Post Purchase Cost				
Recovery/ Logistics Cost	Transport and storage of non stackable chairs plus EOL customer credit	-8	Transport and storage of stackable chairs plus EOL customer credit	-7
Disassembly Cost	Labour cost to remove brackets	-4	Labour cost to separate components	-1
Value recovered	4 steel brackets that can be reused	2	1 reusable steel base, plastic for recycling and 1 reusable bracket	4
Disposal cost	landfill levy to dispose of unwanted components	-1	All components recycled	0
TOTAL Post Purchase Revenue		-9		-4
Life Cycle Cost		1		3
4. Life Cycle Economics				
Market Share	4100/year - poor environmental image		4100/year - good environmental image	
Volume returned at EOL	3280/year		3280/year	
Life Cycle Profit	**£ 11,480**		**£ 15,580**	

Table 4.2: Life cycle economics

In the second case, the chair is produced from material which can be recycled. Therefore in an environmentally conscious market place, such as Holland, the market share is more than that of the previous case. The product uses less expensive materials such as polypropylene at a cost of approximately £700 per tonne [Ashby and Jones 1986]. However, the material requires expensive injection moulding equipment to produce the chair and hence at £23, it is more expensive than the GRP chair. However, by adopting a life cycle economic view of the design, it is shown that its profitability exceeds the GRP chair. This is due to the value recovered from the product at the end of its life cycle, in this case £4. The resultant long term profitability is £15,580 (£7*4,100+£-4*3,280). The life cycle profitability of not taking back the chair at EOL would be £28,700 (£7*4,100), which is considerably more than £15,580. Hence, in this example the company would probably not bother to take back the chair at EOL. Therefore in order to ensure that take back occurred some form of legislation making the manufacturer responsible would be required.

The above example and analysis, although simplified, demonstrates that by having the numbers that constitute the economic life cycle in such a format facilitates in the decision making process. Such analysis demonstrates the reliance upon estimates and assumptions. For example, in the simplified chair example no account is made for overhead recovery. The method of apportionment of such overheads could alter the outcome of the analysis. For instance, returned products could avoid the potential high overheads of the manufacturing company by being subcontracted to a third party. However, there is a risk that by deferring some of the profitability to the future, by designing products which are expensive to manufacture, yet offer a greater return at EOL, then the company may incur financial hardship and cease to exist. The value built into products could then be claimed by another company who chooses to take back the products at EOL. The chair example illustrates the need and value of considering all elements of a product's life to properly assess the economics of the life cycle. However, it also demonstrates some of the problems when trying to apportion costs and make assumptions concerning the future. Appendix F examines the issue of costing systems in more detail.

4.4 The Life Cycle Uncertainty

This simplified example demonstrates the type of evaluations and cost "trade off" that has to be made between design concepts. It demonstrates that integration across life cycle domains is possible through the use of cost. Furthermore, it demonstrates the type of multi-disciplinary data that is required such as sales volumes, disassembly costs, return rates for EOL products, logistical costs and values for EOL materials. However, it does not represent the future value of money. For example, if two design concepts have different life cycles, one with a life cycle of 5 years, the other with a life cycle of 10 years; and the first produces an EOL value of £50 while the second produces an EOL of £300, then a decision maker requires a method of equating both cash flows in terms of the current value of money, taking into account interest rates and inflation. Additionally there is no prediction of values and events in the future. For example, the variability of the value of the returned plastic in the chair is not examined, nor is the variability of the number of returned chairs. No analysis of the variability is undertaken.

In the case of the plastic chair, the market price for recycled plastic may be the most sensitive variable in ensuring profitability. If the market price is unstable then this indicates that the long term profitability may be unstable. For example, if the value of the recovered plastic and steel bracket of the base falls from £4 to £1, then the resultant profit falls to £5,740, making the long term profitability of this case less attractive. In order to guard against this type of variability - which could be detrimental to the profitability of the company - two possible courses of action could be taken. The first is to use a type of plastic which has a track record of consistent EOL value. The second could be for the producer of the chair to purchase equipment to recycle the plastic in-house and use the recycled material in future products. Therefore the value recovered could be consistent at £4, because of the lack of dependency on market forces and the robustness of the profitability improved. Of course, the company could have bypassed the above analysis and increased price to cover any loss, but this would have affected market share and resulted in the profitability being open to greater variability.

The example stresses the importance of life cycle decisions and the diversity and interdependence of perspectives, in this case from manufacturing, purchasing, marketing and sales. From the above one can see that life cycle variables can be split into two categories, those which are controllable and those that are uncontrollable, see Table 4.3. Controllable variables are those which are under the control of the company and can be changed. For example, the structure of the product can be changed by the design team, or the company can control the return rate by varying the amount owners of EOL products receive if they return the products. Uncontrollable factors are those which the company has no power over or it is beyond the economic means of the company to influence. Such uncertainty can be of two types. The first is continually increasing or decreasing over time - the variation for instance, in external markets, material cost, labour cost and disassembly technology. The second type of variation is that which is binary, it either occurs or it does not - for instance legislation, consumer behaviour or the establishment of a recycling infrastructure. With legislation Parliament (or increasingly the EU) plays a key role in the introduction of take back legislation. It can be argued that the powerful and wealthy industry groups are able to form pressure groups and employ lobbyists in an effort to oppose proposed legislation and therefore attempt some form of control over its introduction and form. However, the level of control a company has over such variables still does not allow the company to predict future actions with any confidence. While these variations will occur, designers still have to design whole product lives, without the tools to deal with the associated uncertainty of predicting values and events. This clearly demonstrates one component of a new methodology which does not currently exist in a usable form.

Typical Controllable Variables	Typical Uncontrollable Variables
Product Structure	Take Back Legislation
Use of Materials	Future Value of Materials
Selling Price	Disassembly Technology
Incentive for returning EOL products	Material Technology

Table 4.3: Controllable and uncontrollable variables

In the chair example, a controllable variable would be the selection of a coating on the steel base of the chair. This could be necessary to increase the aesthetic appeal or to provide a protective shield against corrosion. The use of the coating is within the control of the company. It could use a polymer coating, a paint process or a chemical process such as chrome plating (although chrome plating introduces impurity into steel). The uncontrollable variables could be the planned introduction of legislation banning the use of a certain chemical in the plating process. If the chair has a planned production life of 3 years and the legislation is not going to be introduced until 4 years time, then the production route would be acceptable, at the possible expense of adverse publicity and decreased sales. However, if there is uncertainty about the date of introduction (which is often the case with legislation) and a reasonable estimate is between 3 and 5 years, then that variability should be examined with regard to its overall effect on profit. In such a case, the company could conceivably lose a years worth of production and hence sales. Alternatively, because of its impurity level it might be subject to a future and uncertain disposal cost. In order to discover the importance of such variations, it is necessary to provide a breakdown of the contributions to the variability of the profitability. If the contribution is large and the variability of the overall economics is such that it represents too great a risk to the company, then measures could be taken to avoid or reduce the effect of that variable and result in a robust economic life cycle.

The scenario has considered aspects of variability and explained their different types. Without a methodology which assists designers in handling the variability caused by uncertain predictions of future situations, companies can have little confidence in any long term economic performance predictions for a product. The example of the chair excluded the costs of usage, which for such a product are typically low. Obviously for products which require maintenance, the usage costs add a further complexity. For instance, EOL components can be used in the servicing of products, often increasing their potential value.

4.5 Requirements of a New Methodology

From the scenario given, observations from case studies and the literature review, a list of requirements of a new methodology can be outlined. By taking this approach the set of requirements are based upon industrial need.

1. It must represent future cash flows

The economic product life cycle is characterised by cash flows throughout the period of the life cycle from conception through to EOL. Any methodology which aims to be applicable to the life cycle should incorporate within it the means to model the cash flows. Some arguments suggest that future cash flows should be equated to a point in time. One technique, used within investment appraisal techniques to represent future cash flows, is discounting [Lumby 1993]. Such a technique must be applied selectively, because where inflation is stable and low, costs inflate in line with inflation and hence profits over a period of time. However, where inflation is high and unstable, predictions of future rates can be problematic. Life Cycle Costing, as mentioned in section 3.2.2, has been used in projects ranging from construction to weapon systems and is examined in further detail in chapter 5. Hence, any proposed methodology must be capable of dealing with such flows and equating cash flows at different points in time if required.

2. It must indicate which variables have the greatest financial impact in the face of uncertainty

With any future prediction there will always be an element of uncertainty and the issue of life cycle uncertainty was discussed in section 3.4. If the financial performance of the life cycle does not vary widely under a variety of predicted conditions, then such a system is said to be robust. The world is characterised by uncertainty. The management of industries ranging from financial share dealing to construction, have the flexibility to alter their operating strategy in order to capitalise on favourable future opportunities or mitigate losses. For example, management may be able to defer, expand, contract, abandon, or otherwise alter a project at different stages during its useful life. An extreme option in the manufacturing domain would be if companies opted to abandon production completely and realise the resale value of capital equipment and other assets [Trigeorgis 1993]. Once a product has been established within the market place, a company cannot change the structure of the product in the field or escape its legal liability if take back legislation is introduced. However, it is probable that any such legislation would be selective in its approach to dealing with products that are already in the field, allowing companies time to plan the EOL for future products. The introduction of completely retrospective legislation would have the potential to bankrupt whole industries unless new ways of achieving cost effective disassembly for products, not designed for disassembly, was developed.

The idea of robust design is that all (or as many as possible) of the uncertainties during a product's life are considered, examining effects of best case and the worst case. A new methodology must identify the contribution of individual variables to the overall life cycle profit variability. Methods which provide such an analysis are examined in chapter 6.

3. It must be usable and the results easily understood by design teams

The methodology should not require that the effort expended to conduct the analysis prohibit its use. Therefore the methodology should consist of components with which design teams can rapidly produce information from data, in order to influence the decision making process.

4. It must allow "what if" analysis to explore design options

In order to explore various design options, a rapid "what if" analysis is required, one which allows the simple altering of the variables and a life cycle profitability profile to be generated.

5. It must provide confidence that it works

The methodology should, through use in an industrial application, provide evidence that it works.

4.6 Conclusion

The first four chapters have detailed the need and demonstrated the lack of methodologies to support the design team in the uncertainty faced when making design decisions which affect the economic life cycle of the product. Therefore they have met the first two sub objectives set out in chapter 1:

1. to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products; by
2. undertaking a literature and industrial review

This chapter has shown, using a scenario based approach of an industrial case, the requirements of a design decision support methodology by demonstrating the types of decisions involved. It has shown those parts of the design process for which there is currently a lack of support, despite the need highlighted in previous chapters. Such comments generated in the scenario were collected and used to build a set of requirements for an effective methodology, one which should provide practical and usable decision support. The requirements were that it must:

- represent future cash flows
- must indicate which variables have the greatest financial impact in the face of uncertainty
- be usable and the results easily understood by design teams
- allow "what if" analysis
- provide confidence that it works

Having established these requirements, the following chapters use them to develop and validate a new methodology, thus meeting the remaining two sub-objectives of the research to:

3. evaluating and selecting methods to meet the requirements for decision support; and

4. demonstrating that such a system is possible to construct, practicable and beneficial.

5. Life Cycle Costing

The last chapter generated a list of requirements for a new methodology - it must:

- represent future cash flows
- indicate which variables have the greatest financial impact in the face of uncertainty
- be usable and the results easily understood by design teams
- allow "what if" analysis
- provide confidence that it works

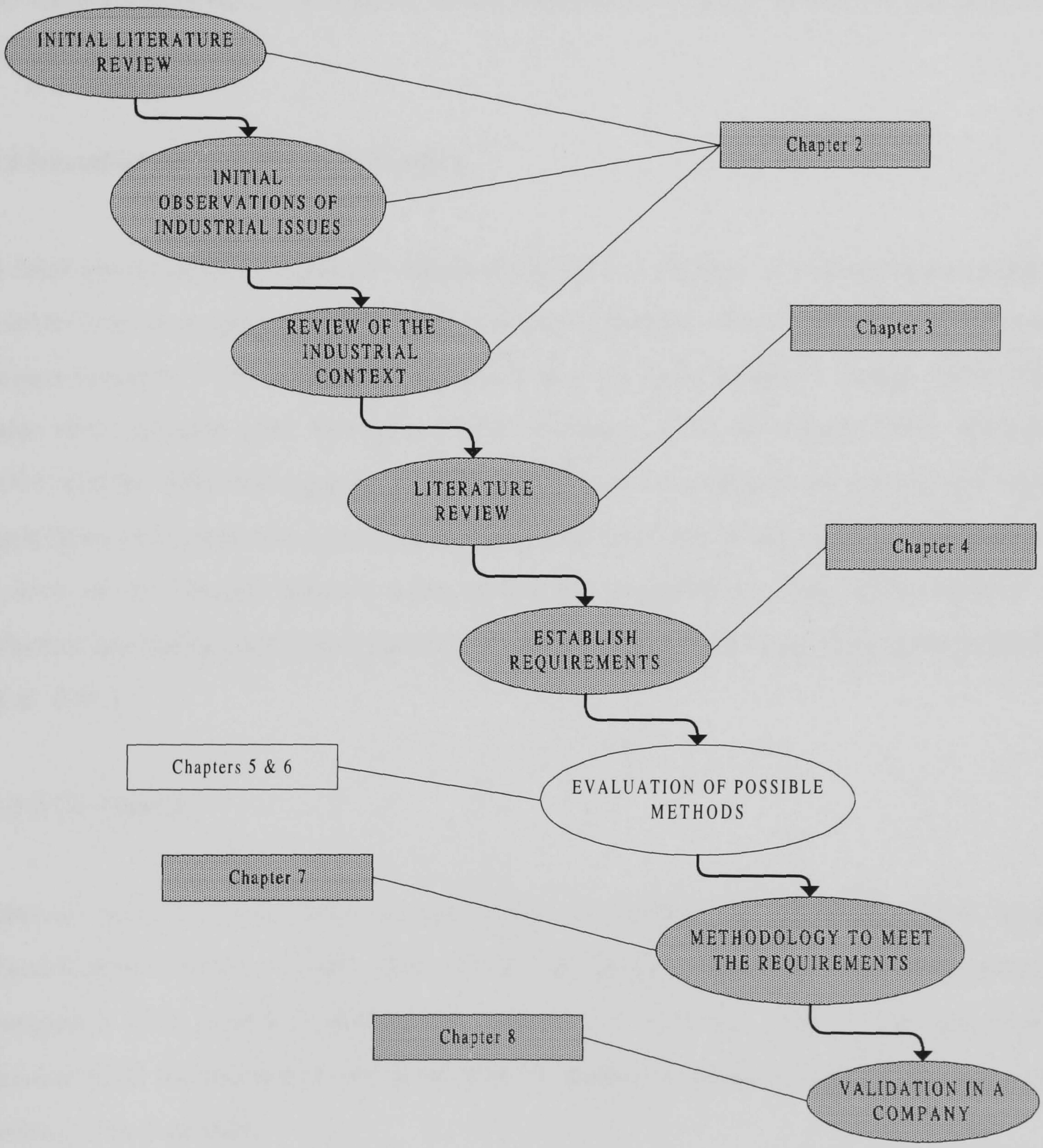

Figure 5.1: Relationship of chapter with research methodology

This chapter focuses on the first requirement - to represent future cash flows. Life Cycle Costing (LCC), which was referred to in chapter 3 appeared to meet this requirement. Therefore the chapter re-examines its suitability, with regard to the scenario described in chapter 4. This will identify shortfalls in the conventional application of LCC in its potential use to meet the third sub-objective set out in chapter 1 of evaluating and selecting methods to meet the requirements for decision support. Additionally a review of how LCC deals with uncertainty is provided in order to examine methods of meeting the second requirement - to indicate which variables have the greatest financial impact in the face of uncertainty.

5.1 Introduction to Life Cycle Costing

A brief history of LCC is given in Appendix B. LCC is defined as a mathematical method used to form or support a decision and is usually employed when faced with a selection of design concepts. LCC is typically applied during the early phases of design [Bull 1993; Dale 1993, Koyama 1993, Gustafsson 1993, Robinson 1993; McGeorge 1993; Ashworth 1993; Griffin 1993; Flanagan et al. 1989]. It attempts to represent all current and future cash flows associated with a product to a single baseline cost [Griffin 1993]. This provides a view of the balance between initial and future expenditures, and allows analysis of whether increasing short term expenditure will result in greater long term gains [Sheldon et al. 1990].

5.2 LCC Models

Dhillion in a literature review of life cycle cost models has provided a LCC model classification [Dhillion 1989]. The models are grouped into two categories; general parametric LCC models which do not centre on a particular product; and specifically defined LCC models which are developed for particular products such as the life cycle costing of new aircraft.

The specifically defined LCC models use explicit estimates of elements and activities to often create a computer model of the product life cycle and the interrelationships of the elements with one another. In comparison, parametric models are used to calculate LCC for products as soon as their general broad characteristics are established. The models use embedded cost estimated relationships derived from similar products, usually by the application of linear equations and past experience.

Dhillion presents a number of general LCC models. These include models developed for the US Navy, Army and Air Force. In addition a number of specific LCC models are described which deal with products such as motors, tank gun systems, diagnostic equipment, switching power supplies, cars, avionic systems, computer software, health care facilities and early warning radar. Of the general LCC models described by Dhillion, only three consider the cost incurred due to end of life scenarios and these are described fully in Appendix B [Dhillion 1989].

5.3 The Future Value of Cash Flows

The following example demonstrates the principle of the future representation of cash flows throughout the life cycle. It compares two products, one which has lower purchase price, but is more expensive to operate; and one which is more expensive, but is more efficient to operate.

	Product A	Product B
Purchase Price	100,000	120,000
Failure Rate per Year	0.04	0.05
Cost of Money	10%	10%
Life	10 years	10 years
Cost of Rectifying a Product Failure	10,000	12,000
Annual Operating Cost	6,500	3,000

Table 5.1: Comparison of the life cycle cost of two products

If the products are compared without any consideration to the time value of money, then product B appears the more economically attractive of the two. However, when the present value of the maintenance and operating costs are considered then economically the products are virtually identical. The present value of money can be explained as follows. Given the choice of £100 today or £100 in a years time, most individuals would choose to take the amount today. This is not as a direct result of inflation or risk, although these are important considerations. It is because, the £100 could be invested, so that it will generate interest. For example, if the interest rate is 6%, then £100 invested today, would be worth £106 in a years time. Therefore in this scenario, a decision maker would be deemed to be indifferent between accepting £100 today or £106 at the end of one year.

The present value, PV of an expenditure T in one years time is therefore:

$$PV = T/(1+r/100)$$

Therefore £100 today has a present value of £94 in one years time, with an interest rate, r of 6%.

At the end of a second year, the present value would be £89,

$$\pounds 100/(1.06)(1.06) = 89$$

This analysis can be carried out ad infinitum, with the present value of T, in n years time with a market discount rate of r,

$$PV = T/(r)^n$$

Therefore the present value of annual cash flows is,

$$PV = T_0 + T_1 / (1+r) + T_2 / (1+r)^2 + \ldots\ldots. + T_n / (1+r)^n$$

So applying the concept of the time value of money to future cash flows indicates that the present value of the cash flow is less than its future forecast value.

Returning to the comparison of the two products:

LCC = Acquisition Cost + Present Value of Maintenance + Present Value of Operating Cost

Product A:

EFC = Expected failure cost per year = probability * cost of a product failure = 0.04 * £10,000 = £400

The Present Value of this cost is therefore = EFC $[(1-(1+i)^{-m})/i]$

where i is the interest rate, m is the useful operating life and $[(1-(1+i)^{-m})/i]$ is known as the present worth factor for a uniform series.

Present Value of failure cost = £400 * 6.15 = £2457.83

using the present worth factor the present value of the operating costs is = £39,939.69

thus,

LCC = 100,000 + 2457.83 + 39,939.69 = £142,397.52

Product B:

EFC = Expected failure cost per year = probability * cost of a product failure = 0.05 * £12,000 = £600

The Present Value this cost is therefore = EFC $[(1-(1+i)^{-m})/i]$

where i is the interest rate, m is the useful operating life and $[(1-(1+i)^{-m})/i]$ is known as the present worth factor for a uniform series.

Present Value of failure cost = £3,686.74

Using the present worth factor the present value of the operating costs is = £18,433.7

thus,

LCC = 120,000 + 3,686.74 + 18,433.7 = £142,120.44

The above demonstrates the fundamental principles of life cycle costing, it shows that after the analysis the two products have very similar life cycle costs. This highlights that the cash flows from each product must be expressed in a common unit, as though the individual cash flows occurred at the same point in time, in order to provide a fair comparison. Discounting of the cash flows using the interest rate as an implicit time value of money allows this comparison to be made. However, in periods of low inflation costs and revenues equally inflate with time and tend to cancel the effect of the other, providing a real difference of only 2 to 3 percent. A further detailed explanation of the time value of money is given in Appendix C.

This section has shown that LCC meets the requirement to represent future cash flows. Its successful use by design teams in industry demonstrates its practical suitability as an underlying component for a new methodology.

5.4 Uncertainty in LCC

Ideally a product life cycle should not provide financial surprises - it should be robust to changing events. Therefore it is important not just to select a product design with the lowest cash outflows and highest cash inflows. However, as discussed in chapters 3 and 4, the future is naturally uncertain and therefore techniques are used in LCC to identify the primary sources of potential uncertainty and identify their likely impact. The following sections examine such techniques.

5.5 Sensitivity Analysis and Probabilistic Methods

There are two basic approaches to dealing with uncertainty in LCC. The first is sensitivity analysis, while the second are probabilistic methods, such as Monte Carlo Analysis. The main difference between the two approaches is that sensitivity analysis does not require probability distributions to be associated with events, whereas probabilistic methods do. However, sensitivity analysis is a special case of a probabilistic approach, in which an equal probability is assigned to each value in the range over which the uncertain parameter is expected to vary.

5.5.1 Sensitivity Analysis

Sensitivity analysis identifies the impact of a change in a single parameter value within a product design. To examine the extent of its effects on the life cycle cost each estimated element of a project's cash flow is varied in turn, whilst all others are held constant. This is known as a certeris paribus assumption or uni-variate, where all other parameters are held constant. A disadvantage is that the technique ignores the possible effects on the outcome on life cycle cost if two or more of the estimated components vary simultaneously.

5.5.2 Probabilistic Methods

The most common probabilistic method used is the Monte Carlo simulation. This type of analysis was derived from gambling casinos and is a means of examining certain types of problems for which unique solutions cannot be obtained. The method uses random numbers allied to the normal probability distribution. As a result it does not generate a singular answer, but provides a general range within which the answer will probably occur. The elements of the life cycle cost are broken down and each element assigned a probability distribution dependant upon the uncertainty associated with that element.

Random numbers are used to generate a figure for that element and the cumulative value of all elements provides an answer. This process is repeated somewhere between 100 and 1000 times dependant upon the number of elements and the accuracy required. The end result is a probability distribution of life cycle costs which approximates to the normal distribution. This provides the decision maker with an indication of the most likely result and a level of confidence provided by the dispersion of the distribution. Hence, this method considers the effect of two or more element varying simultaneously, it is multi-variate.

The main disadvantage of this method is that it focuses on the result and not the contribution of the individual elements or variable of the LCC. Hence, it fails to meet the requirement of indicating which variables have the greatest financial impact in the face of uncertainty, set out in chapter 4. A further disadvantage of the methods is that it is difficult to assign probability distributions to subjective estimates of the future. A report by British Aerospace on their approach to risk, details how they use triangular distributions, with a high, low and mean value rather than the more mathematically precise normal distributions [BAe 1991].

Both sensitivity analysis and probabilistic methods have been used in LCC to deal with uncertainty. However, both have significant disadvantages which limit their practical application. In order to meet the unique requirements of the new methodology a different approach will have to be sought.

5.6 Conclusion

The product life cycle is characterised by cash flows from conception through to EOL. LCC models future cash flows through the product life cycle, equating them to a single point in time through discounting methods. It is a technique which has been widely accepted by the construction and defence industry. This chapter has therefore shown that LCC meets one of the requirements set out in chapter 4, **to represent future cash flows**. Its successful use by design teams in industry demonstrates its practical suitability as an underlying component for a new methodology.

In dealing with uncertainty, LCC traditionally adopts either a sensitivity analysis or probabilistic methods. Both techniques have disadvantages which mean that they do not adequately meet the requirement of **indicating which variables have the greatest financial impact in the face of uncertainty**, as described and set out in chapter 4. Hence other methods which work with LCC must be explored with a view to meeting this requirement.

6. Dealing with Uncertainty

As outlined in the second requirement in chapter 4, a new methodology must **indicate which variables have the greatest financial impact in the face of uncertainty**.

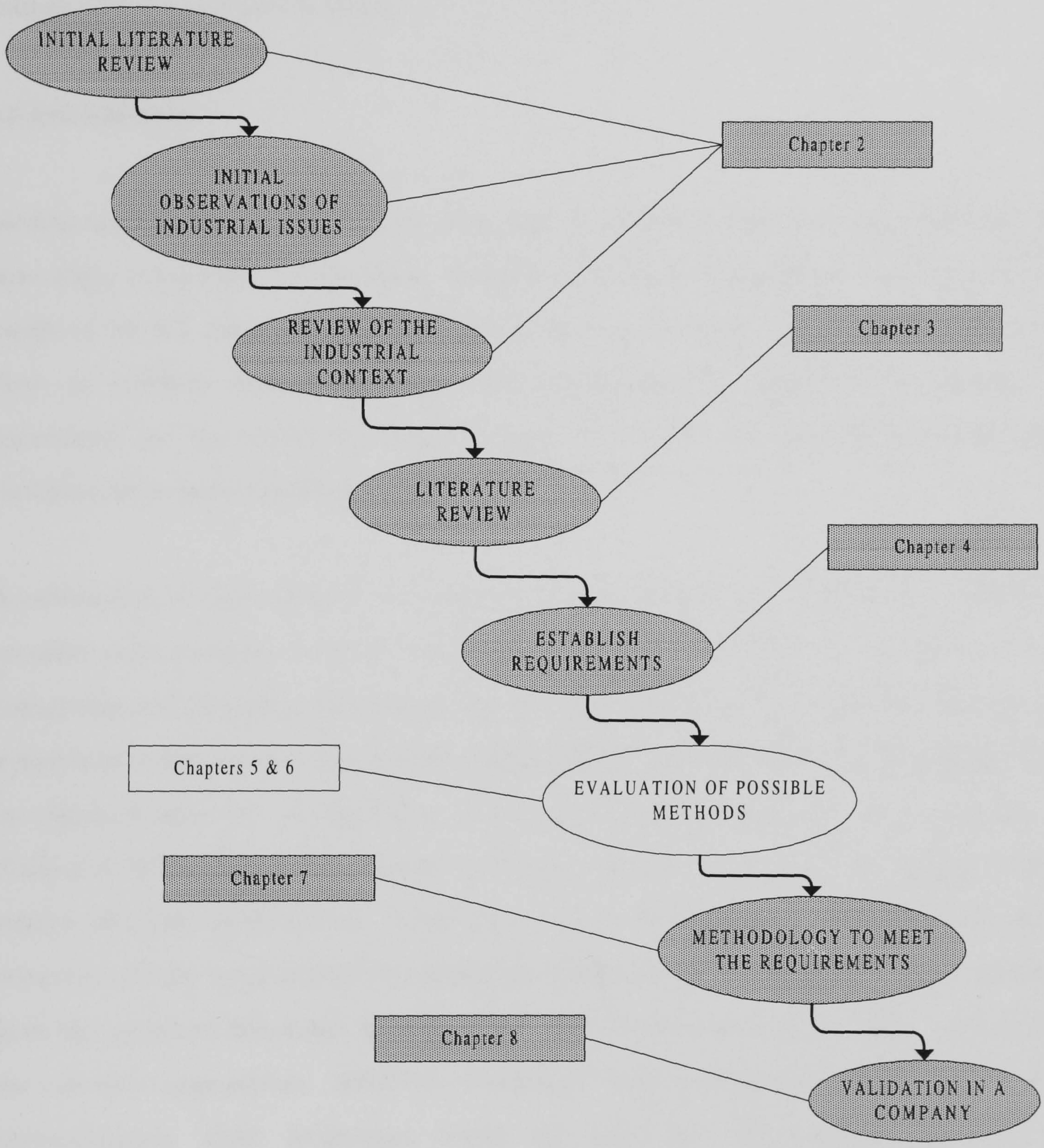

Figure 6.1: Relationship of chapter with research methodology

This chapter introduces and compares two techniques identified from the literature review that appear to meet the above requirement. The first is ANOVA (ANalysis Of VAriance), which is from the Taguchi application of robust design principles and the second is Linear Approximation. The aim of the comparison is to determine which of the two techniques is the most suitable. This chapter shows that Linear Approximation has a number of weaknesses and demonstrates that ANOVA has the potential to be used in a practical manner within Life Cycle Costing.

6.1 Introduction

As discussed in the previous chapter, once a life cycle cost model has been established, the next stage is typically to undertake analysis to examine combinations of inputs to the model of the life cycle cost and the effect on the overall output. If the model of the cash flows is complex then it becomes extremely difficult to understand the drivers of uncertainty and the effects of changes, especially if such changes affect two or more variables of the model simultaneously.

An alternative to such analysis is to undertake a full factorial set of simulations where all possible combinations of input variables within an experiment are included, a time consuming and laborious process. Considering that part of the main objective of the research is to demonstrate that **a new methodology is practicable and beneficial**, such an approach must be avoided due to the excessive time required. For example, to conduct a full factorial experiment with five variable, each with 10 settings would require 100,000 combinations. A literature review for techniques that meet the above objective and the requirement that **a new methodology must indicate which variables have the greatest financial impact in the face of uncertainty**, revealed the possible use of two approaches, ANOVA combined with orthogonal arrays; and Linear Approximation. Both techniques avoid the need for full factorial approach to experimentation and could provide an indication on which variables have the greatest contribution in the face of uncertainty.

The following section compares, through the use of an example, the suitability of ANOVA and Linear Approximation.

6.2 ANOVA - ANalysis Of VAriance

Typically ANOVA is used in experimental design to examine the confidence that can be placed in the results of a partial factorial experiment. The technique determines the variability or variance of the results of an experiment where there are two or more factors with two or more levels. ANOVA provides the contribution to variance of the factors. By understanding the source and magnitude of variance, attempts can be made to establish robust settings of the factors [Roy 1990]. A full description of the mathematics of ANOVA is provided in Appendix D.

Principal to the application of ANOVA is the use of orthogonal arrays. The concept of orthogonal arrays originated in the 1920's with the work of Sir R.A. Fisher who successfully designed partial experiments to determine the optimum treatments for agricultural land to achieve maximum yield. There have since been numerous applications of this approach in the chemical and pharmaceutical industries.

After World War II the allied forces found that the quality of the Japanese telephone system was extremely poor and totally unsuitable for long term communication purposes. In order to improve the system, the allied commander recommended that the Japanese should establish research facilities similar to that of Bell Laboratories in the US in order to develop an improved communication system. Hence, the Japanese founded the Electrical Communication Laboratories (ECL), with a man named Taguchi placed in charge of improving the R&D productivity and product quality. Taguchi observed that a great deal of time and money was wasted in conducting experiments [Roy 1990]. By building upon the work of Fisher, Taguchi developed the idea of experimental design.

If in an experiment there are 15 factors which can have two levels (e.g. on or off), then there are 2^{15} (32,768) possible combinations. To undertake a full set of experiments may be exorbitant in terms of time and money. The use of fractional factorial experiments simplify the experiment by investigating only some of the possible combinations, in this case 16 experiments. This approach saves considerable time and money but requires rigorous mathematical treatment, both in the design of the experiment and in the analysis of the results. Even if there are just 7 factors at two possible levels, then a full factorial experiment would require 2^7 or 128 experiments. By using an orthogonal array only 8 experiments are required.

An analogy that describes the efficiency of the Taguchi method is that of attempting to catch fish. Traditionally, an elaborate method of trawling the area would be required, which would be expensive in terms of time and money. The Taguchi approach is rather like a fish finder, indicating, through a trial survey, which areas are most likely to yield fish.

6.2.1 Worked Example of ANOVA

The following is a simple example of ANOVA. The example is based on the scenario where a product is sold in the market place with an annual sales revenue varying between £170 and £180. The service cost of the product, to be met by the manufacturer is expected to vary between £150 and £200, with the discount rate, to represent future cash flows, of between 3% and 20%.

There are three factors at two levels:
Factor A = annual sales revenue over 3 years, with level 1, £170 and level 2, £180
Factor B = annual service cost, over years 2, 3 and 4 with level 1, £150 and level 2, £200
Factor C = discount rate, with level 1 being 3% and level 2 being 20%

Therefore an experimental design strategy must be formulated. A suitable orthogonal array is the L_4 , with four experiments.

L_4 ARRAY	FACTORS		
EXPERIMENT No	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Table 6.1: An L_4 array

These figures are then used within a life cycle costing analysis.

$$LCC = Y = A + (A-B)/(1+C) + (A-B)/(1+C)^2 + (A-B)/(1+C)^3 + (-B)/(1+C)^4$$

The results of each experiment are listed in Table 6.2. Note that in this scenario there is a real threat that the company could make a financial loss.

L_4 ARRAY	FACTORS			RESULT
EXPERIMENT No	A	B	C	Y (£)
1	170	150	3	93.3
2	170	200	20	10.35
3	180	150	20	170.9
4	180	200	3	-54.3

Table 6.2: Experimentation results

There are four resultant life cycle costs from the experiment:

$$Y_1 = 93.3$$
$$Y_2 = 10.35$$
$$Y_3 = 170.9$$
$$Y_4 = -54.3$$

The totals of the factors, which is the summation of the outputs, for a level of the factors are:

$A_1 =$

the sum of the LCCs at the lowest value of A, annual sales revenue = 93.3+10.35 = 103.65

$A_2 =$

the sum of the LCCs at the highest value of A, annual sales revenue = 170.9-54.3 = 116.6

$B_1 =$

the sum of the LCCs at the lowest value of B, annual service cost = 93.3+170.9 = 264.2

$B_2 =$

the sum of the LCCs at the highest value of B, annual service cost = 10.35-54.3 = -43.95

$C_1 =$

the sum of the LCCs at the lowest value of C, discount rate = 93.3-54.3 = 39

$C_2 =$

the sum of the LCCs at the highest value of C, discount rate = 10.35+170.9 = 181.25

The total variation is expressed as the sum of the square of all trial results, minus the correction factor. The correction factor is the square of the total of the factors, divided by the number of experimental runs. Therefore:

$$C.F. = T^2 / n, \text{ where } T = (Y_1 + ... + Y_n)$$
$$C.F. = 12127.5$$

$$S_T = (Y_1^2 + ... + Y_n^2) - C.F.$$
$$S_T = (Y_1^2 + ... + Y_n^2) - (Y_1 + ... + Y_n)^2 / n$$

$S_T = (93.3^2 + 10.35^2 + 170.9^2 + -54.3^2) - (93.3 + 10.35 + 170.9 + -54.3)^2 / 4$

$S_T = 28839.8$

The total variance of each factor is:

$$S_A = A_1^2 / N_{A1} + A_2^2 / N_{A2} - C.F.$$
$$= 103.65^2 / 2 + 116.6^2 / 2 - 12127.5$$
$$= 41.9$$

$$S_B = B_1^2 / N_{B1} + B_2^2 / N_{B2} - C.F.$$
$$= 264.2^2 / 2 + -43.95^2 / 2 - 12127.5$$
$$= 23739$$

$$S_C = C_1^2 / N_{C1} + C_2^2 / N_{C2} - C.F.$$
$$= 39^2 / 2 + 181.25^2 / 2 - 12127.5$$
$$= 5058.8$$

As a check the error variance can be calculated, which should be 0,

$$S_e = S_T - (S_A + S_B + S_C)$$
$$= 28839.8 - (41.9 + 23739 + 5058.8) = 0$$

although this has no input to the analysis.

The percent contribution of each factor is a ratio of the factor sum to the total, expressed in percent.

$$P_A = S_A * 100 / S_T$$
$$= 41.9 * 100 / 28839.8$$
$$= 0.15\%$$

$$P_B = S_B * 100 / S_T$$

$= 82.3\%$

$$P_C = S_C * 100 / S_T$$
$$= 17.5\%$$

This demonstrates that factor A, the variance in the annual sales revenue contributed to 0.15% of the variability of the profitability, while the annual service cost contributed 82.3% and the discount rate 17.5%. Therefore the main area of concern would be the annual service cost.

In this example the average profitability of the product is £55, however it was shown that there was at least one situation where a financial loss of £54.3 was incurred. ANOVA identifies that the greatest contributor to this variance is the service cost. Therefore it would be good practice to eliminate this variation by designing a product whose service cost distribution was more limited, perhaps between £160 and £180, rather than £150 to £200. This reduction in variability of cost may even be considered sufficiently valuable to the company to allow extra cost to be built into the product at the design stage.

A smaller contributor to variance is the discount rate, an external factor dependant upon the interest rate, which of course is impossible for the company to control. It may be the case that after reducing the variability of the warranty cost, that the company is still unhappy with the overall variability. In this case a third party maintenance company could perhaps take on the warranty liability and therefore eliminate the variability to the company. Such actions will increase the robustness of the product profitability.

The requirement of a new methodology, as stated in chapter 4, was that it **must indicate which variables have the greatest financial impact in the face of uncertainty**. The above example demonstrates that ANOVA is suitable to the requirement of a new methodology in that it indicates in a practical method which variables have the greatest financial impact in the face of uncertainty. In the literature search undertaken, there was no evidence which indicated the application of ANOVA in the domain of life cycle cost models and hence its use is novel. The application of ANOVA has been traditionally focused upon engineering design, and its advantages have been shown by the example to be equally applicable to the requirements set out for a new methodology [Clausing 1991].

6.3 Linear Approximation

With an analytical model of the LCC, it is possible to apply linear analysis to predict the performance of such a model. References to the sensitivity of capital recovery, to changes in the variables defining it, refer to the use of differential calculus to deal with uncertainty [Morris 1960]. Brown expanded on the work of Morris and that of non-linear control theory to develop a method using quasi-linearisation which provides an analytic sensitivity analysis to supplement the sensitivity analysis, described in chapter 5 [Brown 1968]. In quasi-linearisation an operating point or benchmark is identified and then the sensitivity analysis is conducted by evaluating the first order linear deviations using the formula for the total differential from calculus:

$$dq = (df / dx)\, dx + (df / dy)\, dy + (df / dz)\, dz + \ldots..$$

where:

$$q = f(x, y, z, \ldots..)$$

In reality it is possible to represent differentials as small incremental steps:

$$dq = \Delta q$$

$$dx = \Delta x$$

$$dy = \Delta y$$

$$dz = \Delta z$$

Morris uses the example of the analytical model of an investment with a life of between six and seven years and a salvage value of between £7000 and £8000. The equation for the life cycle cost is:

$$CR(i) = (P-F)(A/P\ i,n) + Fi$$

Where:

CR(i) is the life cycle cost

P is initial cost

F is salvage value

i is interest rate

A/P i, n = Annual Equivalent Factor, the value of an immediate annuity which lasts for N years, where the prevailing rate of discount is i, and which has a present value of £1.

Examples of the most likely values are as follows:

$$P = 72000$$

$$F = 8000$$

$$i = 7\%$$

The partials with respect to initial cost and salvage value; and the sensitivity, obtained by substituting in the most likely values are:

*d*CR(i)/*d*P = (A/P i, n) = i / (1-(1+i)$^{-N}$) = £0.205406 per £1 increase in P, the initial cost

*d*CR(i)/*d*F = - (A/P i, n) + 1 = £0.105406 per £1 increase in F, the salvage cost

*d*CR(i)/*d*n = (P-F)(1n(1+i))(A/P i, n)(A/F i, n)/i =

£1,341.3 per year increase in the duration

*d*CR(i)/*d*i = F + A/B = £509.58 per 1% increase in the discount rate

Where:

A = (P-F)(A/P i, n)/i

B = 1 - (n(A/F i, n)/(1+i))

A/F i, n is the annual value of an annuity which lasts for N years, where the prevailing rate of interest is i, and which has a terminal value of £1.

Using an assumption of probability that the units given are the most likely, then the most sensitive variable is the life of the project. A decrease of one year of the life of the asset will result in an additional cost of £1,341.3. However, if it is likely that the project will not increase or decrease by a day, which equates to £3.67 per day, then the most sensitive variable is the potential change in the interest rate by 1%, which has an impact of £509.58.

The result of the most probable life cycle cost is obtained by substituting the most likely values into the equation:

$$CR(i) = (P-F)(A/P\ i,n) + Fi$$

$$CR(i) = (72000 - 7000)(\ 0.1\ /\ (1-(1+0.1)^{-7})) + 7000(0.1) = £14,051$$

The least favourable situation, when the life of the asset is reduced to 6 years and the salvage cost rises to £8,000 results in a life cycle cost of:

$$CR(i) = (72000 - 8000)(\ 0.1\ /\ (1-(1+0.1)^{-6})) + 8000(0.1) = £15,495$$

This figure can also be derived using the Linear Approximation of the partial differentiation:

$$dCR(i) = (1000)(-0.105406) + (-1)(-1341.3) = £1,236 + £14,051 = £15,287$$

However, a small error is encountered due to the linear technique, which does not take into account the higher orders of the above equation. Higher orders are at the centre of LCC, with the use of interest rates to represent the future value of money and hence this could potentially be a weakness in the Linear Approximation approach.

The examples given in the above sections have demonstrated that both ANOVA and Linear Approximation meet the requirement of a new methodology, that it **must indicate which variables have the greatest financial impact in the face of uncertainty**. However, the two approaches require a more detailed examination to understand which of the two is superior in this environment.

6.3.1 A Comparison of ANOVA and Linear Approximation

Consider the method applied to the earlier example used within ANOVA. The example was based on the scenario where a product was sold in the market place with an annual sales revenue variation of between £170 and £180. The service cost of the product, to be met by the manufacturer was expected to vary between £150 and £200, with the discount rate to represent future cash flows of between 3% and 20%. So:

Factor A = annual sales revenue over 3 years, with level 1, £170 and level 2, £180
Factor B = annual service cost, over years 2, 3 and 4 with level 1, £150 and level 2, £200
Factor C = discount rate, with level 1 being 3% and level 2 being 20%

$$LCC = A + (A-B)/(1+C) + (A-B)/(1+C)^2 + (A-B)/(1+C)^3 + (-B)/(1+C)^4$$

If the average values are used as the starting point for calculating the partial equations :

A (annual sales revenue)	= £175
B (annual service cost)	= £175
C (discount rate)	= 8.5%

$dLCC/dA = 1 + 1/(1+C) + 1/(1+C)^2 + 1/(1+C)^3 =$ £3.55 per pound increase in A

$dLCC/dB = -1/(1+C) - 1/(1+C)^2 - 1/(1+C)^3 + -1/(1+C)^4 =$ £-3.27 per pound increase in B

$dLCC/dC =$
$(A-B)/(1+C)^2 + 2(A-B)/(1+C)^3 + 3(A-B)/(1+C)^4 + -4B/(1+C)^5 =$ £4.66 increase per 1%

This analysis provides the sensitivity of the factors about the average.

The total profit at these average levels is:

$$LCC = A + (A-B)/(1+C) + (A-B)/(1+C)^2 + (A-B)/(1+C)^3 + (-B)/(1+C)^4$$

$LCC = 175 - 175/(1.085)^4 =$ £48.73

If the value of the life cycle cost is required for the outer limits of the variables, then this can be determined using Linear Approximation.

Assume for one set of outer limits the values of the variables are:

A (annual sales revenue) = £180

B (annual service cost) = £200

C (discount rate) = 3%

and that:

For A: 180 (average value) -175 = 5

*d*LCC/*d*A = 5*3.55 (per pound increase) = 17.75

For B: 200 (average value) -175 = 25

*d*LCC/*d*B = 25*-3.27 (per pound increase in B) = -81.75

For C: 8.5 (average value) -3 = 5.5

*d*LCC/*d*C = -5.5*4.66 (per 1%) = -25.63

= (17.75-81.75-25.63) + 48.73 (the LCC for the average variable values) = -40.9

This provides a value for the profitability at one extreme of the anticipated values using Linear Approximation. This should now be compared with the LCC equation to validate whether such Linear Approximation is valid with higher order terms of the LCC equation.

Therefore using the LCC equation and the values of £180(A), £200(B) and 3%(C):

$$LCC = A + (A-B)/(1+C) + (A-B)/(1+C)^2 + (A-B)/(1+C)^3 + (-B)/(1+C)^4$$

$$= 180 + -19.42 + -18.85 + -18.3 + -177.7 = -53.57$$

Compared with -40.9 for the LCC given by Linear Approximation it would appear that such a method does not deal well with higher order terms in the equation. Such higher order terms are essential for LCC, where the cash flows are discounted by an order dependant upon the year and therefore such a method is not suitable for this purpose. In addition, the level of calculus and analysis required for this simple example demonstrates the lack of practicality in taking this approach. Designers, given their busy roles, would be additionally burdened.

Recalculating the partial equations, with the previous figures in brackets and using the outer limits as the start point:

A (annual sales revenue)	= £180
B (annual service cost)	= £200
C (discount rate)	= 3%

dLCC/dA = £3.83 (3.55) per pound increase in A

dLCC/dB = £-3.72 (-3.27) per pound increase in B

dLCC/dr = £ 7.99 (4.66) per 1% increase

If the previous values for the partial equations are compared (figures in brackets) it can be seen that there is a large change in the value of the partial equation for the third factor, the interest rate, which contains the higher order components in the LCC equation. This further confirms the problems of using Linear Approximation.

To summarise, Linear Approximation has a number of disadvantages:

- it produces errors because of the higher order terms in the cost model
- it requires a degree of calculus
- the output requires further analysis and effort to determine the contribution to LCC variance

Following the comparisons in this chapter, it has been shown that although ANOVA and Linear Approximation both meet some of the requirements of a new methodology, ANOVA is the most suitable due mainly to its practical applicability.

6.4 Conclusion

A review of techniques that deal with the type of uncertainty outlined in chapter 3, revealed ANOVA and Linear Approximation as possible solutions. This chapter has shown through worked examples that whilst Linear Approximation has a number of disadvantages, ANOVA has the potential to be used in a practical manner within Life Cycle Costing. ANOVA therefore meets the second requirement of a new methodology, that it must:

- **indicate which variables have the greatest financial impact in the face of uncertainty.**

7. A Methodology for the Design of Economically superior Life cycles

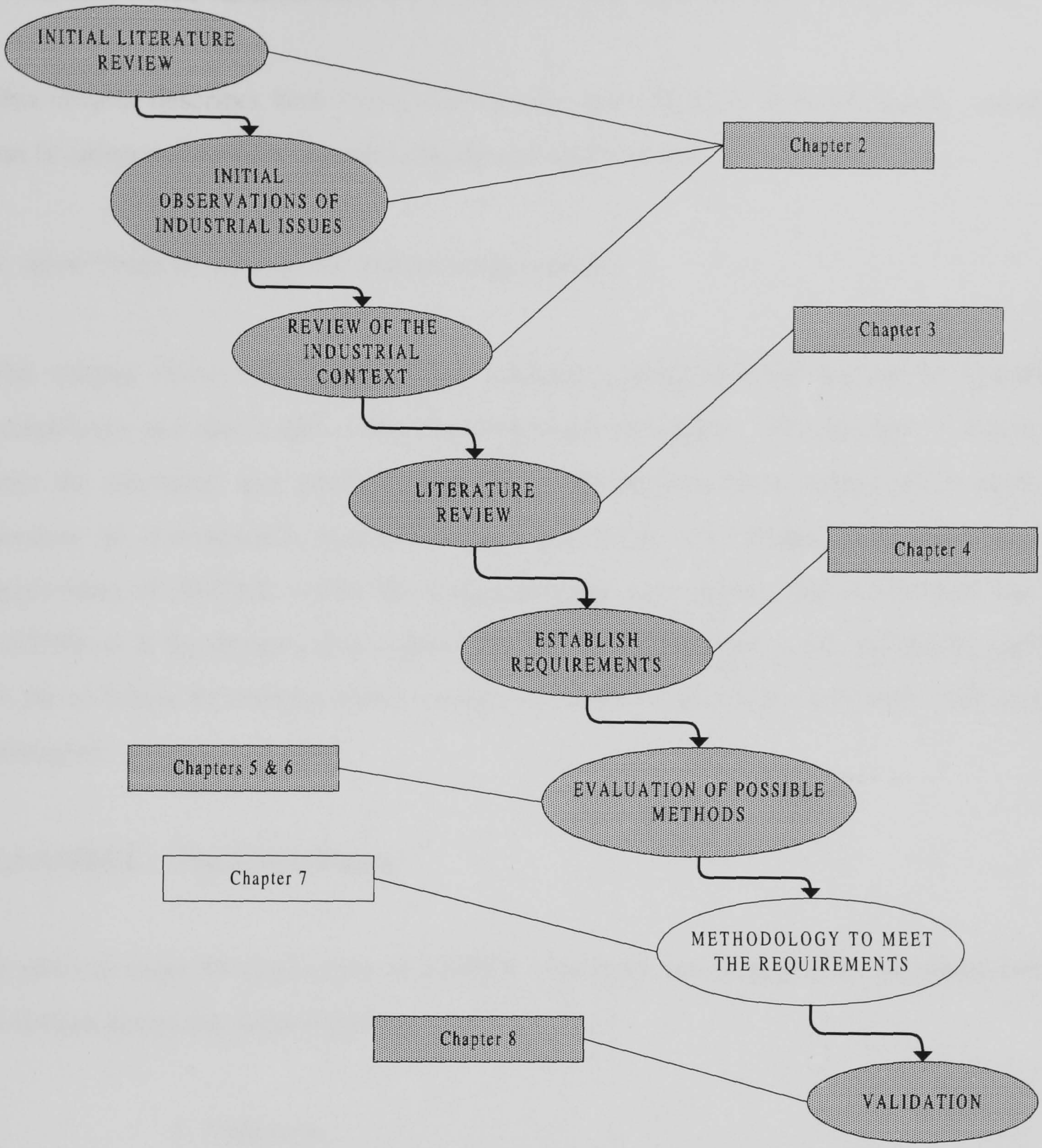

Figure 7.1: Relationship of chapter with research methodology

This chapter introduces the proposed methodology generated from the research. The methodology is known as AMDEL - A Methodology for the Design of Economically superior Life cycles. The previous chapters introduced Life Cycle Costing and ANOVA as components that met some of the requirements for a new methodology set out in chapter 4, e.g. that it must:

- represent future cash flows
- indicate which variables have the greatest financial impact in the face of uncertainty

This chapter describes how Life Cycle Costing and ANOVA, with additional elements, can be integrated to meet the third requirement that it must:

- allow "what if" analysis to explore design options

The chapter shows that AMDEL has coherently integrated the previously identified components and that it uses a structured approach to analysis. Theoretically, it describes how the structured and practical approach is broken into three stages which work to produce an economically superior product life cycle. The chapter also discusses the application of AMDEL within the design process. It is shown that the primary use of AMDEL is in the design process; however, it is also shown that it can be equally applied to the re-design of existing product ranges or to examine product take back and service strategies.

7.1 AMDEL - The Three Stages

In order to make the application of AMDEL structured and manageable, the methodology is broken down into three stages.

1. Definition
2. Model Generation
3. Experimentation and Analysis

The aim of taking a structured approach is based upon the practice of problem solving [PA 1996]. Naturally, it is more effective to break the problem into easily solvable parts [Murchison and Baird 1996]. This is typical within project management, where a large piece of work is broken down into a structure consisting of easily manageable tasks. The tasks added together form the total work required to complete the project [Matin 1994]. By breaking AMDEL into stages, the methodology becomes structured and hence more practical.

7.1.1 Definition

The conceptual or initial phases of the design process are primarily concerned with the generation of solutions to meet the stated needs of the consumer and legislation. The generation of new concepts can take place at the product, sub-assembly or component level. Thus, it may not be possible to significantly improve the overall design concept of a product, although many opportunities for improvement may exist at the sub-assembly or component level. Therefore once a range of solutions have been generated, the next task for the design team is to evaluate the solutions, select the most suitable and attempt to optimise its constituent parts. In this environment the design team requires support in evaluating the best concept in terms of its life cycle profitability for the company, whilst meeting the user requirements. The design team is faced with a number of questions. How do they choose the best concept? How can they justify their choice? How can they show that other concepts were not as good? By the application of a model of the economic life cycle, AMDEL can provide valuable support to the design team at this stage of concept design.

Within the AMDEL methodology the scope of such a model must be defined with clear boundaries, at the start of the design process. This is analogous to the process of boundary setting in LCA which was examined in chapter 3 [Murchison and Baird 1996]. All companies and products are different, therefore it is useful in this definition stage to identify the positioning of the proposed product within the market place. Some products will clearly be unsuited to EOL product take back. For example, does the market place require frequent design modifications, which will effect the ability to use spare components from EOL products in service applications? Such a classification may be based upon the following:

i) Expensive or cheap product

ii) Long or short life

iii) Service requirements and usage of spares

iv) Consumer buying criteria (looks, cost, reliability, brand name etc.)

v) Simple or complex design and manufacture process

vi) Frequency of design changes

vii) Legislation and safety standards

viii) Disposal routes

If a company concludes that EOL product take back is unlikely to occur then it should focus effort on increasing the efficiency of manufacture, assembly and possibly service. Section 7.2 describes the use of methodologies, such as DFM/A, that can be used for this purpose.

Unless this definition phase is undertaken, confusion will occur within the design team concerning the scope of the model. For instance, here are some example questions that a design team will be faced with when considering the take back of future products. If components have second or third generation life cycles in future products, will this be taken into account by the value at the end of the first life, or will the analysis be conducted over the three generations? If the analysis is conducted over three generations, how will the design of future products be restricted by the need to reuse "old" components? Some components are subject to legislation which places restrictions at product EOL. Will these components be remanufactured before being reused? These example questions show that different boundaries for the model will have differing implications, therefore it is important to have a basic definition from which members of a design team can work. Such a definition allows common understanding of the boundaries of the model, upon which discussion and debate can be centred.

In order to assist the definition stage AMDEL provides a generic life cycle model, which builds upon Life Cycle Costing. The provision of such a model provides a structure and direction about which the design team can work. The model divides the definition into sections of the life cycle, allowing the various members of the design team to focus on their relevant area. Although in no way is this model meant to be prescriptive, it will typically accelerate the definition process of AMDEL. This is similar to the computer modelling of manufacturing systems, where generic computer models are provided by simulation packages. These models are then modified, using input from process specialists, to match reality. The provision of such models reduces the amount of modelling time and provides direction for the modelling process [Gregory 1995; Ardhaldjian and Fahner 1994]. Hence, AMDEL provides a model termed the Life Cycle Economic Model:

$$LCE=\Sigma^{T}_{t=0} PV\{[(Sp + TBr) - (MPc + MAc + OSc + Wc + TBc + RMc)]*Vol \}$$

where:

T is the time period in years to EOL
PV is the present value
Sp is the price charged for the product
TBr is the revenue generated from taking back the product, in terms of material or components
MPc is the raw material procurement cost
MAc is the manufacture and assembly cost
OSc is both the internal and external operational and support cost of the product
Wc is the warranty cost to the producer
TBc is the cost of product take back, including logistics and incentives
RMc is the remanufacture cost
Vol is the volume of sales in each year

Although the equation is generally aimed at a product, there is no restriction upon it being applied to individual components. However, the philosophy of the methodology is that it should consider the whole product in order to direct the focus of the design team upon those individual components which are critical to the economic viability of the product life cycle.

The model provides a starting point for a design team. If further elaboration is required this is entirely possible. For example, if the market is sensitive to energy usage then the energy costs of the product in use could be related to the volume of sales, with a greater in use cost resulting in a decline of sales. Once the definition is complete then the next stage of AMDEL, modelling can begin. However, unless the definition is agreed and signed off by all member of the design team, then modelling of the life cycle becomes unstructured and the results difficult to analyse. For example, the raw material cost could be reduced by using recycled material. However, if the manufacturing process cannot use recycled material then the analysis from the model will be invalid.

As the conceptual stage of design finishes, the design team should have an evolving design concept, with the components that make up the design gradually becoming established. As with most design tools, the earlier AMDEL can be applied, then the greater chance it will have to influence the life cycle cost [Brophy 1994]. However, there is a potential source of conflict in that at the early stages of concept design information concerning detailed components may not, due to uncertainty, be precise. Hence, the design team will be required to use their best efforts to produce highest and lowest estimates for variables based upon their knowledge and experience. AMDEL recognises this problem of uncertainty and guides the design team on where to focus the most effective effort. To demonstrate this principal consider the following simplistic example. The manufacturing cost of a concept product may be estimated to be between £9 and £10, with the take back cost between £6 and £15. AMDEL may show that due to a low predicted return rate of between 5% and 10% that any effort in eliminating the variance of the take back cost will have little effect on the overall profit variability. However, because the manufacturing cost is incurred by all products and if it is assumed that the selling price is £11, then AMDEL will show that effort is best applied by the design team in reducing the variability of the manufacturing cost as this is critical to the profitability of the product.

This shows that the definition stage does not require precise information. AMDEL itself will state which estimates need to be handled with care and where more effort can be put into increasing the confidence in the upper and lower estimates of a particular variable. However, as the design evolves and AMDEL is iteratively re-applied then the design team may need to re-visit its definition of the product in order to focus, considering the above example, on the detailed components that will make up the manufacturing cost. This concept is further developed in the experimentation stage of AMDEL.

Definition

- ***common understanding***
- ***estimates required due to uncertainty***
- ***data knowledge increases with time in design process***
- ***iterative***

Model Generation

Experimentation and Analysis

7.1.2 Model Generation

The definition phase provides a starting point which results in an equation that represents the economics of a product design. The final phase of AMDEL involves experimentation and analysis, but before this can be undertaken a model of the equation has to be established so that raw data can be applied to the model and outputs observed. In a simple LCE, an equation can be used to manually undertake experimentation. One of the requirements of a new methodology, was that **it must allow rapid "what if" analysis**. However, an LCE model typically comprises of a vast amount of data which has to be collated. The manual recording of such large amounts of data in the current age of computer tools is not acceptable. Hence, in order to allow the efficient use of AMDEL it is appropriate to adopt some form of computer aided assistance. This at its most simple can be in the form of spreadsheets and at its most sophisticated in the form of discrete event simulation. Spreadsheets have the advantage of requiring a low degree of expertise to establish and are in-expensive, with costs below £100. However, the output of data can be difficult to interpret and the model can be difficult to manage as its complexity increases.

Computer simulation on the other hand is expensive, with a typical system, including the required training, costing in excess of £15,000. Typically, using simulation takes longer to develop a model. However, discrete event simulation is aimed specifically at the modelling of time based events, which is applicable to the product economic life cycle. It is widely accepted within industry, especially within Business Process Re-engineering initiatives, to examine rapidly the effects and performance benefits of the re-design of business processes [Ardhaldjian and Fahner 1994; Robinson 1994; Butler et al. 1995; Business Intelligence 1994; Knutton 1994]. As a result, the past ten years has seen the emergence of a number of specialist software packages. Rapid "what if" analysis is the main benefit of using computer simulation, with complex models easy to modify [Dwyer 1997; Ardhaldjian and Fahner 1994; Pritsker 1994]. A model can be run over a simulated time period and stopped at any point in that period to be analysed. The output of the model can be provided graphically and in the form of comprehensive statistics, which display performance over time. The graphical display in the form of animation provides confidence that the model operates as expected and is functioning correctly [Dwyer 1997; Butler et al. 1995; Business Intelligence 1994; Ardhaldjian and Fahner 1994]. If the output was in the form of a set of values, the levels of which (even though they may be correct) appear to be at odds with the expectations of the users, then there will be a lack of confidence in the model. However, if the reason for a strange set of outputs can be demonstrated by animation, then either the users can accept that the output is indeed correct or recognise that there is an error with the logic of the model. Such errors can then be corrected and the model re-run as a check.

Although there is a vast difference in cost between spreadsheets and computer simulation, extra manual resource may be expended on the analysis and construction of spreadsheet models and this may outweigh the initial high cost of discrete event simulation - £15,000, the cost of the package and training, is typically less than half a man year of effort.

For the purposes of the use of AMDEL in this research, discrete event simulation was adopted because the University had access to the package and because it is the best tool to satisfy the objectives of the research. A simpler application would have taken longer to develop and would not have had the benefit of such powerful animation. The software selected for use within AMDEL is SIMPLE++, the latest generation of simulation software, launched in 1994. SIMPLE++ is an object-oriented, graphical user-interface simulation system. It has been used to model a wide variety of complex systems and business processes Examples include manufacturing, assembly, storage and transport systems. SIMPLE++ stands for the **SIM**ulation in **P**roduction, **L**ogistics and **E**ngineering design and its implementation in C++. The system was chosen primarily because of its ease of use and rapid processing power. The software can model products as individual entities, which accrue cost and value as they pass through the elements of the life cycle. Therefore the cost elements are not defined by equations. If a design feature is changed, then this is represented by altering the attributes of the entities, not an equation. The use of discrete event simulation to modelling the economic life cycle is novel, rapid and effective.

The model generation is often the most time intensive period. Despite the user friendly nature of the current generation of simulation tools, a trained operator is required to construct the model. The definition stage of AMDEL will identify the input parameters and relationships between these parameters. Once an initial model is established and iterative trial runs performed, a comparison is made to compare performance against the model definition stage to ensure that the model performs in the manner expected. For example, the design team may request changes in the parameters, perhaps the selling price, which will result in a change in the volume of products sold. This often provokes debate on whether the output matches that which would be expected in reality. It may be that a change in the logic of the model is required to mimic this relationship. Once a valid model has been established the next stage within AMDEL is to undertake structured experimentation. This method of using simulation is classically the way it is applied in the manufacturing domain [Dwyer 1997; Pritsker 1994].

Definition

- *common understanding*
- *estimates required due to uncertainty*

- data knowledge increases with time in design process

- iterative

Model Generation

- selection of software

- modelling expert

- iterative steps to match reality

Experimentation and Analysis

7.1.3 Experimentation and Analysis

Typically the LCE model is complex with many variables. Hence it becomes extremely difficult to understand the drivers of uncertainty and the effects of changes, especially if such changes affect two or more variables simultaneously. Hence in chapter 6, an approach to experimentation using orthogonal arrays was introduced, as part of the process of ANOVA. Once the model has been defined and a computer model generated, structured experimentation can be undertaken using an orthogonal array. Depending upon the number of variables identified from the definition stage, a standard orthogonal array can be selected based upon the criteria set out in Appendix E. If there are three variables, then an L_4 array can be used, where 1 represents the lowest or worst estimate and 2 the highest or best estimate:

L_4 ARRAY	FACTORS		
EXPERIMENT No	A	B	C
1	1	1	1
2	1	2	2
3	2	1	2
4	2	2	1

Table 7.1: An L_4 array

The experimentation then follows the settings given in the array. So for the first experimental run of the model, variables A, B and C would be set at their lowest levels. The array dictates that four experimental runs are undertaken. At the end of these runs, there will be four results which are then used to identify which of the factors has the greatest contribution to the overall variability. A further detailed description and a worked example is provided in section 6.2.1 of chapter 6.

The first run using ANOVA should be at a high level of abstraction, there is little use modelling the intricate complexities of individual components. At this level ANOVA will indicate which areas or sub-assemblies have the most impact on variability. Once these are identified the model complexity can be increased in those areas which are critical to variability and the AMDEL process re-run. The number of variables that are considered will increase and therefore a new array will be required. This time AMDEL will consider the variability of the sub-assemblies or components. At this point, the analysis will begin to pinpoint which exact components contribute most to the overall economic variability. To demonstrate this principle consider the example given earlier in the chapter in section 7.1.1. The example contained three variables, manufacturing cost, return rate and return value which were set at two levels. The manufacturing cost of a concept product was, due to uncertainty estimated by the design team to be between £9 and £10, with the take back cost estimated to be between £6 and £15. AMDEL had shown that due to a low return rate, estimated to be between 5% and 10%, that effort in eliminating the variance of the take back cost would have little effect on the overall profit variability. However, because the manufacturing cost was incurred by all products and if it was assumed that the selling price was £11, then AMDEL demonstrated that effort was best applied by the design team in reducing the variability of the manufacturing cost as this was critical to the profitability of the product.

EXPERIMENT No	Manufacturing Cost	Return Rate	Take Back Cost	RESULTANT PROFIT
1	£9	5%	£6	£150,000
2	£9	10%	£15	£100,000
3	£10	5%	£15	£50,000
4	£10	10%	£6	£60,000
ANOVA - % contribution to profit variability	70%	15%	15%	£50,000 to £150,000 variability

Table 7.2: Experimentation results

Hence, in the above case AMDEL would be re-applied in order to focus on the areas of concern, such as manufacturing cost variability, which contributes to 70% of the resultant profit variability. Therefore the detailed components that make up the manufacturing cost are demonstrated to be the most effective for the design team to concentrate, in order to remove variability and strive towards a robust profit margin. Let us assume that the manufacturing cost can be sub-divided into five sub-assemblies, A, B, C, D and E. Hence, there are now five sub assemblies that make up the manufacturing cost in addition to the return rate and take back cost, F and G respectively. Hence, the model now has eight variables, which require experimentation. Therefore an L_8 array is now required to be used for experimentation.

L_8 ARRAY	FACTORS						
EXPERIMENT No	A	B	C	D	E	F	G
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Table 7.3: An L_8 array

The array now dictates that the definition phase of AMDEL is re-visited to obtain the best and worst estimates for the values of the sub-assemblies. The manufacturing cost in the example amounted to between £9 and £10. Effort is now required to examine these figures in detail. The result of this may show that sub-assembly:

A = £2 to £2.40

B = £2.80 to £2.95

C= £0.80 to £1.10

D = £1.60 to £1.75

E = £1.80 to £1.80

As the example is simplified it can be seen that sub-assembly A is where effort should be focused to reduce variability. The variability of £1 clearly affects the financial variability of the product. However, the ability to eliminate variability is often not possible in reality and hence attention may be required on the other 4 sub-assemblies to reduce their combined variability. However, the variability of the other four sub-assemblies may be below that of the contribution of the return rate or the take back cost and hence the focus of effort for the design team may change. Therefore although the analysis in this simplified example may be obvious there is still a need to re-run experimentation with the model a total of eight times with an increased level of detail required in the modelling of the sub-assemblies. Obviously the model would first have to be expanded to include the increased level of detail. However, the important issue to note is that the model was not expanded to the greatest detail initially. Therefore effort was not wasted by the design team in defining best and worst estimates to a high degree of detail

The variables in the model would be set according to the levels specified in the array:

L_8 ARRAY	FACTORS							
EXPERIMENT No	Subass 'A	Subass 'B	Subass 'C	Subass 'D	Subass 'E	Return Rate	Take Back Cost	RESULTANT PROFIT
1	£2	£2.80	£0.80	£1.60	£1.80	5%	£6	
2	£2	£2.80	£0.80	£1.75	£1.80	10%	£15	
3	£2	£2.95	£1.10	£1.60	£1.80	10%	£15	
4	£2	£2.95	£1.10	£1.75	£1.80	5%	£6	
5	£2.40	£2.80	£1.10	£1.60	£1.80	5%	£15	
6	£2.40	£2.80	£1.10	£1.75	£1.80	10%	£6	
7	£2.40	£2.95	£0.80	£1.60	£1.80	10%	£6	
8	£2.40	£2.95	£0.80	£1.75	£1.80	5%	£15	
% contribution to profit variability	35%	8%	18%	8%	0%	15%	15%	£50,000 to £150,000

Table 7.4 : Experimentation results

Obviously the major area of effort for the design team should be sub-assembly A. Further detailed analysis is required, perhaps by re-applying AMDEL to the next component level to try and reduce the uncertainty concerned with this sub-assembly. Perhaps such analysis might show that the greatest contribution to the variability of sub-assembly A is a particular component which is subject to uncertain future environmental legislation. Once such a component has been identified action can be taken, either by changing the design so that the contribution of the variable is minimised or avoided; or by re-focusing effort to reduce the variability of the other variables.

Hence, if the variability of sub-assembly A cannot be reduced, then the next area of focus for the design team should be sub-assembly C. Again, if the variability cannot be reduced by the design team, then effort should be focused on the return rate, the take back cost or the combination of the two remaining sub-assemblies B and D. The variability of the take back cost could be reduced by using a third party to take back future products at a set price whilst offering consumers incentives for the return of products. However, the design should examine the effects on profitability.

This section has shown that in applying AMDEL the design team can focus effectively upon those areas of a product design which contribute the most to overall profit variability. It clearly demonstrates that analysis is only applied in detail where it is required and that by using the information provided, the design team can exert effort in attempting to re-design products and ensure that their life cycles are economically superior.

Definition

- *common understanding*
- *estimates required due to uncertainty*
- *data knowledge increases with time in design process*
- *iterative*

Model Generation

- *selection of software*
- *modelling expert*
- *iterative steps to match reality*

Experimentation and Analysis

- ***use of high level model and data***
- ***analysis using model and ANOVA identifies problem areas***
- ***effort focused on greatest areas of profit variability***
- ***iterative analysis with definition and model generation***
- ***information used by design team to create economically superior products***

7.2 Boundaries of AMDEL

The above has examined the use of AMDEL, however consideration should be given to how it relates with existing design methodologies, such as Design For Manufacture/Assembly - DFM/A [Boothroyd 1993; Boothroyd 1994], Design For Serviceability - DFS [Subramani and Dewhurst 1993; Gershenson and Ishii 1991] and Design For DisAssembly - DFDA [Simon et al. 1992], which evaluate a proposed design for optimisation in a particular perspective of the life cycle. The benefits of application of DFM/A have been fully documented in terms of simpler product structures with reduced part count and lower initial product cost. For instance, in some cases in the interests of efficiency design for assembly specifies the use of fasteners such as adhesives and rivets over threaded fasteners. This is in direct opposition to the requirement for efficient disassembly [Dewhurst 1993], a common feature of product service and product recycling. However, even between these two perspectives there is a conflict because in service applications the products must be carefully disassembled while in recycling they are often required to be broken apart for fast separation.

AMDEL considers the whole life cycle of the product and the associated economics. Section 7.1.1 identified analysis that should be performed prior to the adoption of AMDEL. For instance, if there is little chance of products being returned then it would not make economic sense to concentrate on disassembly efficiency. Therefore a company may, if there is no potential legislation enforcing EOL product take back, decide to concentrate of DFM/A.

AMDEL deals with the comparative value of money over time. A disadvantage of current Design For DisAssembly methodologies [Simon et al. 1992; Ishii and Mukherjee 1992] is that they model themselves on DFA systems which use standard or customised data sets to create the basic costs of assembly of disassembly. However, it may be unreasonable to base the calculations of disassembly cost on current values and expect these components to achieve these values at the end of the product's useful life. AMDEL therefore focuses a design team on where effort is best applied along with the appropriate "design for" methodology.

AMDEL can also be applied to re-designing an existing product range in an attempt to ensure that it is robust to future events. This is particularly useful where a company does not wish to spend large amounts of capital required to produce a new product. Although the application of AMDEL will not be as effective, benefits can be achieved by examining product take back and in-service strategies. For instance, a future warranty cost, for which the manufacturer is responsible and which is highly variable with product age, could be mitigated by offering customers an incentive to replace existing products of a certain age with a new product. Alternatively, a manufacturer could consider that the uncertainty of an uncontrollable variable such as legislation is too great a risk and hence, through a commercial agreement, make a third party responsible for taking back and disposing of its EOL products.

7.3 Conclusion

This chapter has introduced the AMDEL methodology and its three stages:

1. Definition
2. Model Generation
3. Experimentation and Analysis

Using these three stages, it has been described how AMDEL can be used to identify the main drivers of financial variability within a product life cycle design and how AMDEL can provide decision support, in order to achieve a robust economic design. The three stages describe how AMDEL uses computer simulation to produce an economic life cycle model which has ANOVA as its main component. The AMDEL methodology is therefore shown to be both coherent and integrated. This chapter has also described how AMDEL meets the third requirement of a practicable methodology that, is:

- **it must allow "what if" analysis to explore design options**

It has been shown that AMDEL can be used primarily within the process of a new product design, and also that of reviewing an existing product range or in examining product take back and in-service strategies.

8. Validation

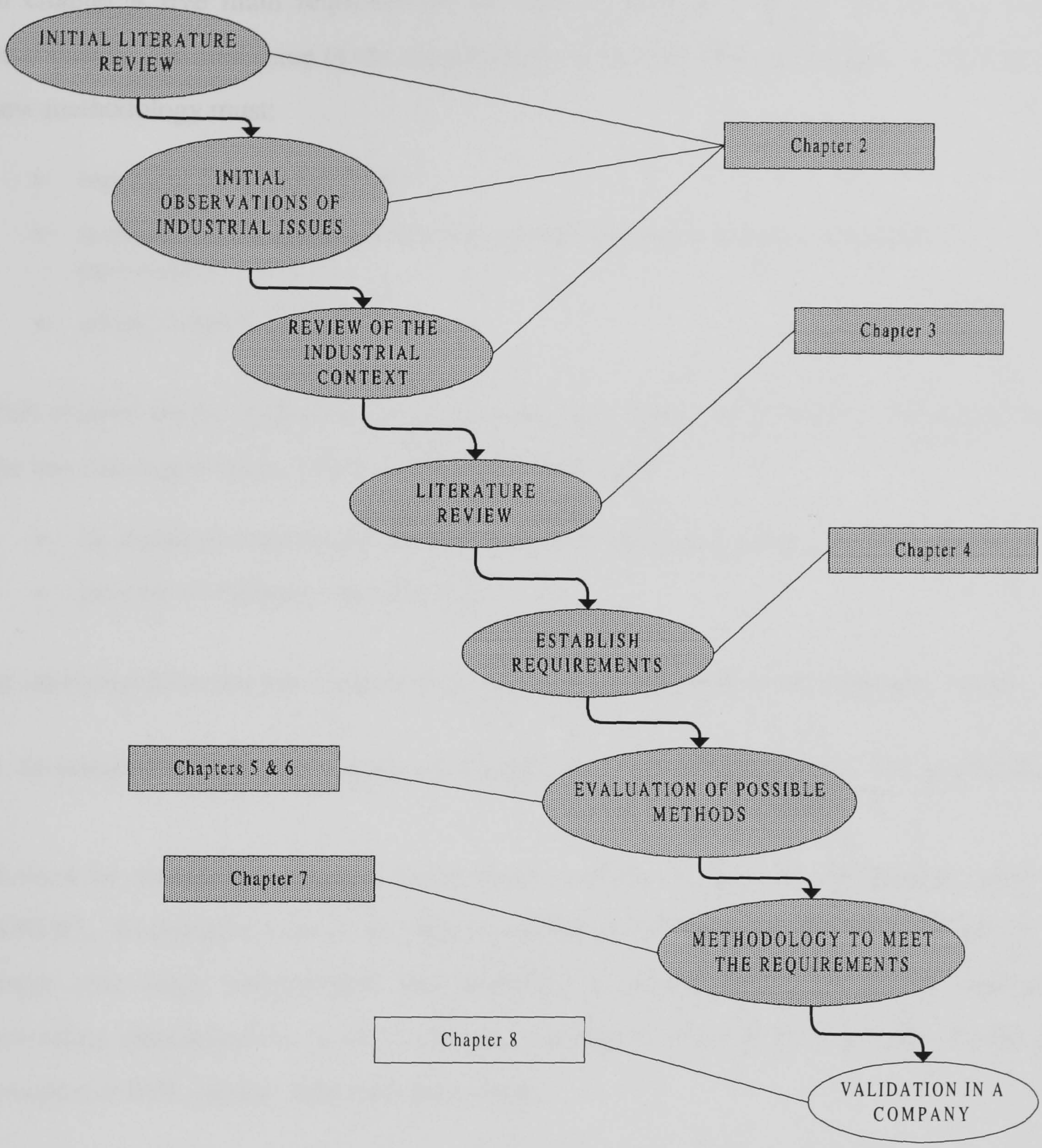

Figure 8.1: Relationship of chapter with research methodology

The first three sub objectives of the research were to:

1. to understand the requirements for a decision support methodology that influences the design of product life cycles to create economically superior products; by

2. undertaking a literature and industrial review; and

3. evaluating and selecting methods to meet the requirements for decision support

In chapter 4 five main requirements for such a decision support methodology were established. The first three of the requirements were addressed in chapters 5, 6 and 7 - a new methodology must:

- represent future cash flows
- indicate which variables have the greatest financial impact in the face of uncertainty
- allow "what if" analysis.

This chapter, by the application of an industrial case study, demonstrates compliance with the last two requirements, that a new methodology must:

- be usable and the results easily understood by design teams
- provide confidence that it works.

In satisfying these last two requirements, the final sub objective of the research is met:

4. demonstrating that such a system is possible to construct, practicable and beneficial.

It must be noted that one case study cannot validate a general methodology such as AMDEL. Companies vary in an almost infinite number of combinations. However, a single case study demonstrates that AMDEL is logical and viable in the particular prevailing circumstances, in this scenario, a domestic white goods company facing the prospect of EOL product take back legislation.

8.1 Validation

The initial stages of the research were validated by the consistency that was established between observations made from site visits and interviews with companies involved in product take back and literature reviews. This validation process is detailed in chapter 2 and led to the following conclusions which are listed in chapter 1:

- Legislation is moving towards making manufacturers responsible for their products at the end of the products life.

- The automotive, electronics and domestic white goods markets will be among the first industries to experience such legislation.

- Some electronics and automotive manufacturers have already established product take back and recycling schemes.

- During product design there is little or no consideration within these companies of the economic implications of product take back issues.

- The greatest opportunity to influence the life cycle profitability of a product is at the early design stages.

- The use of current costs to consider the EOL scenario is a potential hazard because the future involves uncertainty about events and values.

The above observations directed the area for the case towards electronics companies and in particular producers of domestic white goods. Hence, the case study was undertaken with a leading world-wide manufacturer of washing machines, refrigerators and freezers. The company, with a turnover in excess of £500m, employ over 1,500 personnel and is part of a group of companies which is involved in the production of domestic white goods. The company has three sites located in the UK.

As mentioned in chapter 7, AMDEL can be applied to the design of a new product or, as in this case, retrospectively to an existing product range. Following initial discussions with the company it was decided to focus the application of the methodology on an existing product range, their market leading washing machine. The company felt that as the application was a pilot study, it would be more beneficial to apply AMDEL retrospectively for three reasons:

1. They were already considering a study into take back of the selected washing machine. In fact they refurbished damaged new stock and refurbished old motors on an ad-hoc basis depending upon service requirements, in a facility employing 20 personnel. Prior to committing to a full product take back operation, the company wanted to be sure that their strategy for taking back their existing products in the market place would not place an unacceptable financial burden upon the company, by examining the effect on a single product range.

2. They had access to detailed component and sub-assembly data for the existing product range and therefore AMDEL could be applied quickly. The company were anxious to understand the benefits that the application of AMDEL could provide. If AMDEL had been applied to a new product design, then the length of the analysis would have had to be extended through the concept and detailed design phases, in order to derive the full benefit from its application. With a timescale in the order of 3 or more years for new product design, it was felt preferable to apply AMDEL retrospectively to an existing product range. Inevitably, such an approach, whilst necessary due to time constraints, limited the validation of the methodology, in that it was not applied to a new product design. Hence, it was not possible to demonstrate that AMDEL influenced the new product design process and that at EOL greater financial benefits were realised.

3. There was potential scope for re-design of the product range. Although the company was committed to taking back the existing product range, it had decided that if the output of AMDEL identified areas for improvement within the design, then such changes would be considered in a re-design of the product range. Therefore, the approach took a value engineering perspective in order to extend the life of the existing product range.

The main aim of the company was to undertake the project in order to understand the benefits of take back and investigate extending the value of using AMDEL across all product ranges. In undertaking this work they wanted to demonstrate to the Government that they were proactively examining and implementing product take back.

In applying AMDEL retrospectively, the main aim of the research was partially met. The two requirements, that a new methodology must be:

- be usable and the results easily understood by design teams
- provide confidence that it works

were investigated.

8.2 AMDEL - The Case Study

The company gave the case study a high profile, with the involvement of senior management from design, manufacturing, cost accounting, logistics, service and refurbishment. The investment by the company in the project in terms of resourcing amounted to £50,000 of time. The management team appointed a full time Environmental Specialist to co-ordinate the project within the company. Access to sites, personnel and data was unlimited, although confidentiality agreements limited disclosure of some of the findings. However, in some cases, data such as the prices for scrap materials, had to be provided by third party sources. The services of a company cost accountant were sought to correctly apportion overhead rates. A disassembly laboratory was established at Cranfield University and extensive use was made of the University's computing facilities, namely UNIX based RS6000 workstations. A team of 3 people were involved from the University.

AMDEL consists of three distinct stages, as set out in chapter 7:

- Definition
- Model Generation
- Experimentation and Analysis

These three stages were followed in the case study. Representatives from design, manufacture, logistics and service were involved at all stages through the use of interviews.

8.2.1 AMDEL - Definition

The first stage of AMDEL is to define the scope of the analysis. In defining the scope the following assumptions were established:

- The project would model one life cycle of an existing product range, including return, scrap values and the value obtained for reusing components.
- The future value of money was not discounted, because AMDEL was applied retrospectively to current products that are under consideration for take back in the short term. As discussed in chapter 5, in the short term, costs inflate in line with profits.
- The products were only returned via the current direct home-delivery route - either when a customer ordered a new replacement product or when the customer contacted the company and requested that they remove the EOL product. Where products were disposed of via other means, such as refuse sites, there were no current agreements for return. Therefore the volume of returned machines was determined by the home-delivery process.
- Old components were <u>not</u> used in newly manufactured machines (due to standards laid down by regulatory authorities such as BEAB and product liability law). In general, such standards will always limit the use of old components in new products, with few exceptions. Values for reclaimed components were derived from possible use in service applications for similar products.
- The logistics structure for EOL machines had adequate capacity (i.e. lorries and warehouses would have space for returns).

A product was disassembled, at the laboratory at Cranfield University, in order to gain an appreciation of the product (to establish disassembly precedence and times; component masses; materials types; and order of disassembly). A video film of the operation was made and a number of photographs taken to demonstrate problems encountered during disassembly. Such problems were fed back to the company and are described in Appendix G.

The initial definition of the life cycle economic model focused on five variables, which were deemed to be uncertain:

- EOL Component Values
- Disassembly Cost
- Logistics Costs
- Disposal Cost
- Return Rate

A large proportion of the data for estimates was obtained from the company from its various UK sites, in particular from the design and manufacturing departments, which held detailed information and knowledge on the product, such as the bill of material. However, where there was a lack of knowledge or data, then third party organisations were used.

The highest values for the components of the product at the EOL were taken as being their value as used service replacement items. The lowest values for components were taken as the scrap values. The uncertainty of scrap material values for the product was approached by examining the fluctuations in the past year's material prices, taking worst and best cases as boundaries.

Therefore the following estimates of the variables were made:

Variable	Best Estimate	Worst Estimate
EOL Component Values	£34.3 / product assumed reuse of suitable components in service applications	£3.55 / product assumed scrap value for all components
Disassembly Costs	£2.98 / product based on efficiency improvements and improved tooling	£6.27 / product based on current practice
Logistics Costs	£4.63 / product based on current practice	£5.56 / product based on increasing costs of legislation on transportation
Disposal Costs	£0 / per product based on current disposal cost	£2 / product based on possible levy
Returned Stock	80% of home deliveries are returned at EOL	20% of home deliveries are returned at EOL

Table 8.1: Variable estimates

8.2.2 AMDEL - Model Generation

At the centre of AMDEL is the computer based model of the product life cycle. The generation of the life cycle model was the most time intensive part of the project, taking a minimum of 40 man days, mainly due to validating the model within the various company departments that had supplied data. This was because various members disagreed with some of the initial data values and demonstrates the need to conduct the definition phase of AMDEL. For example, it was argued that some of the logistics cost should be zero, because previously un-utilised return logistics route would be used. However, other members argued that there would be increased fuel and loading/unloading costs. In a further example, the service function argued that refurbished motors had a reliability level equal to new motors and could be used in new production, however manufacturing were concerned about consumer image and would not allow their use in new products.

The model was based on a hierarchical structure, built up of four main areas:

- manufacture;
- logistics;
- in-service;
- recycling/refurbishment.

At the highest level of abstraction, the model represented the production sites, the logistics network, the market-place and the take back facility. The decision was taken with the company to model the take back facility in detail, because this area would have to cope with potential increased volumes and because they wanted to know at which stage to stop disassembly. The take back facility was costed as an independent "jobbing shop", with a low overhead rate. This was undertaken to avoid the high overheads of the domestic white good manufacturer. By using a considerably reduced overhead costing rate, the profitability was greatly enhanced. The manufacturing sites were broken down into the manufacturing facility and the storage area for newly manufactured products. The logistics network represented the distance between sites, warehouses, customers and the return logistics route for EOL machines. By modelling the logistics network in terms of: the capacities of the lorries; their average speeds; their average distances; and by including the physical constraints of the warehouses, any potential bottlenecks or lack of resources could be identified. For instance, it was possible to establish the physical capacity requirement and the associated cost of holding EOL inventory at warehouses. The in-service area of the model represented the purchase and use of products by consumers. This area of the model also represented the level of product reliability in terms of the failure rates. Additionally, the penalty costs of disposal were also modelled.

The model represented the dynamics of the take back facility, which included the utilisation of resources, lead-time and buffer levels required for a certain level of returned machines. It also provided a graph displaying value recovered versus cost expended. This is shown in Figure 8.2, where a sharp rise is observed in the value of the materials and components recovered from the product against the time expended in dismantling - approximately 13 minutes. This is the point where a high value component was removed from the product. Personnel from the service function provided calculations on the remaining life of high value items in order to ensure that they would not have a high failure rate, associated warranty cost and negative effect on company image. Dependant upon material scrap values and the demand for refurbished components, the profile was subject to change. The model provided a quick graphical analysis of the disassembly economics and gave an indication of the amount of value obtained if disassembly was further continued by expending more cost. By changing the precedence of the disassembly in the model, the profile could be altered, allowing for experimentation to achieve an optimal disassembly approach.

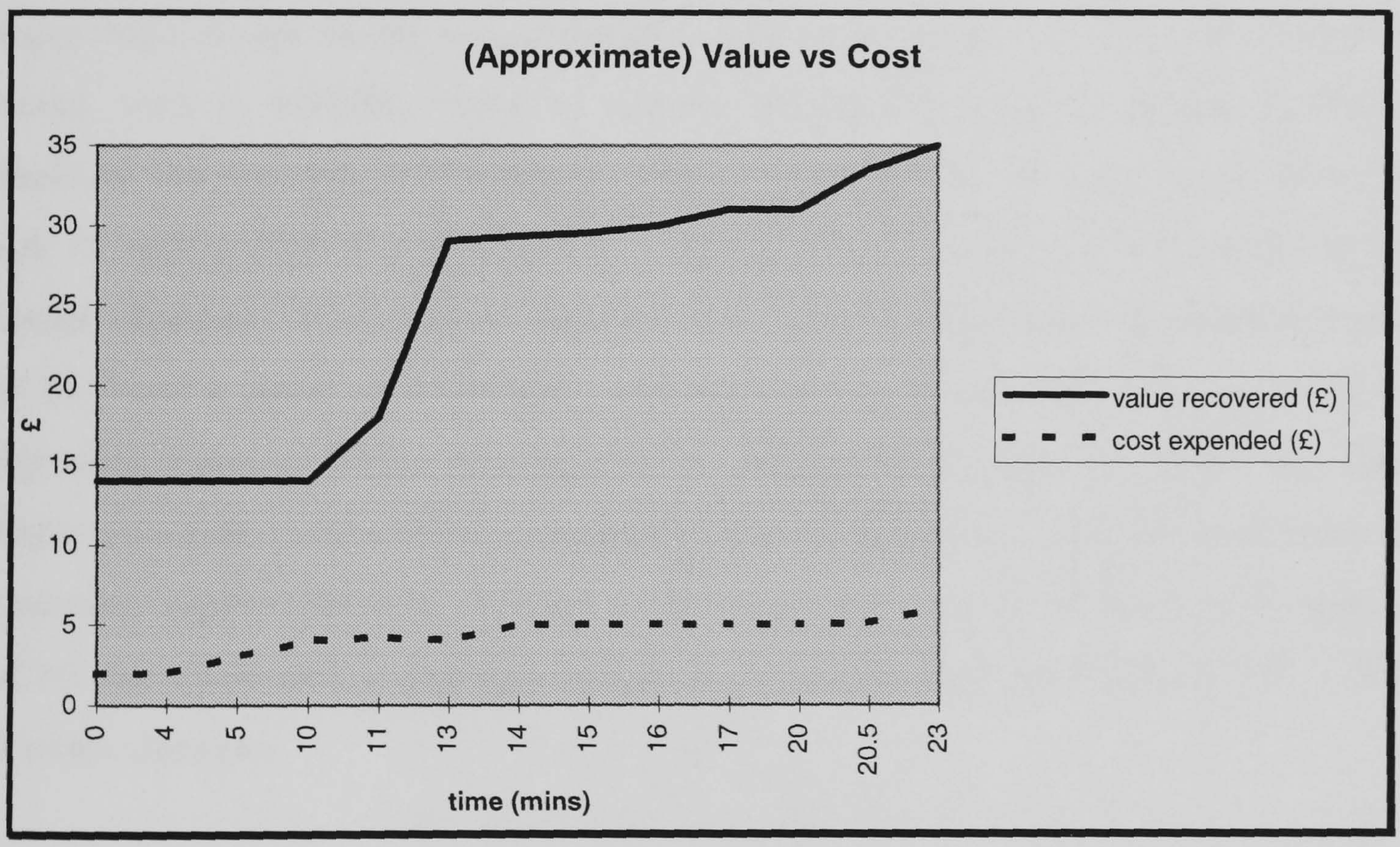

Figure 8.2: Profit profile for disassembly of the product

The figures for the material and component values in the model were held in spreadsheets and by varying these values the overall effect on profitability could be obtained. In order to maintain an accurate model, these spreadsheets would have to be updated regularly. A future beneficial development of the tool would be the provision of on-line data sources.

The model was established for use in this case study, but because the logistics network was now modelled it could easily be amended for use on other products produced by the company. The ability to make "what if" changes to the product design and simulating almost instantaneously the effects of such a change over the next few years in terms of profitability was a powerful concept to the company. As a result they have invested more time in developing further models for other products. Whilst such models provide an evaluation of design concepts, it should be remembered that given an infinite amount of time a company can design a perfect product. However, there is a point at which a trade off has to be made and the proposed design signed off. This is because a company typically has limited resources to invest in product design which have to be recovered and the consumer will not wait an infinite amount of time. The value achieved in improving a design should exceed the cost expended. The use of a life cycle economic model, such as AMDEL, helps to identify the point at which a design should be finalised. For example, if the analysis identifies that profitability will vary between £1 and £3 million then it is probable that the company would not invest further in the design. However, if the analysis demonstrates that profitability will vary between a loss of £0.5 and a profit of £1 million, then it is likely further design effort would be expended. Once a product has entered the market place, reaches maturity and sales begin to decline, further effort is expended in the design process in order to increase its consumer appeal. However, the costs of design changes start to influence other aspects of the life cycle and so emerges Darwinian Evolution with the development of new product concepts.

8.2.3 AMDEL - Experimentation and Analysis

Using the method outlined in chapter 6, an L_8 orthogonal array was used to conduct the experimentation of the model. This array was chosen because it can deal with up to 8 variables at two levels and was therefore adequate for 5 variables at 2 levels. The use of the array meant that only 8 experimentation runs of the model were required, compared with 64 for a full factorial experiment. The experimentation of the model, as prescribed by the orthogonal array resulted in the following outputs:

EOL Comp' Value (£)	Disassembly Costs (£)	Logistics Costs (£)	Disposal Costs (£)	Returned Stock (%)	Profit/Loss per Year
3.55	6.27	5.56	2	20%	£-225,000
3.55	2.98	5.56	2	80%	£-270,000
3.55	6.27	4.63	0	20%	£-7,000
3.55	2.98	4.63	0	80%	£-64,000
34.3	2.98	5.56	0	20%	£25,000
34.3	6.27	5.56	0	80%	£360,000
34.3	2.98	4.63	2	20%	£-200,000
34.3	6.27	4.63	2	80%	£180,000

Table 8.2: Experimentation results

The disassembly costs comprised solely of the labour costs involved. Hence, in order to deal with the increased volumes of product take back it was assumed that additional human resource would be recruited. The additional tooling costs were deemed negligible because of their low cost. Therefore the disassembly cost was levied at a fixed rate per machine and not variable based upon volume. The volume of returns at EOL varied from approximately 4,000 (20%) to 15,000 (80%) per annum.

Using the ANOVA approach outlined in chapter 6 on the above data the following analysis was then completed. The contribution of the individual variability of the component values, disposal costs, disassembly methods, returned stock and logistics costs to the overall profit variability (-£270,000 to £360,000) is shown in Figure 8.3.

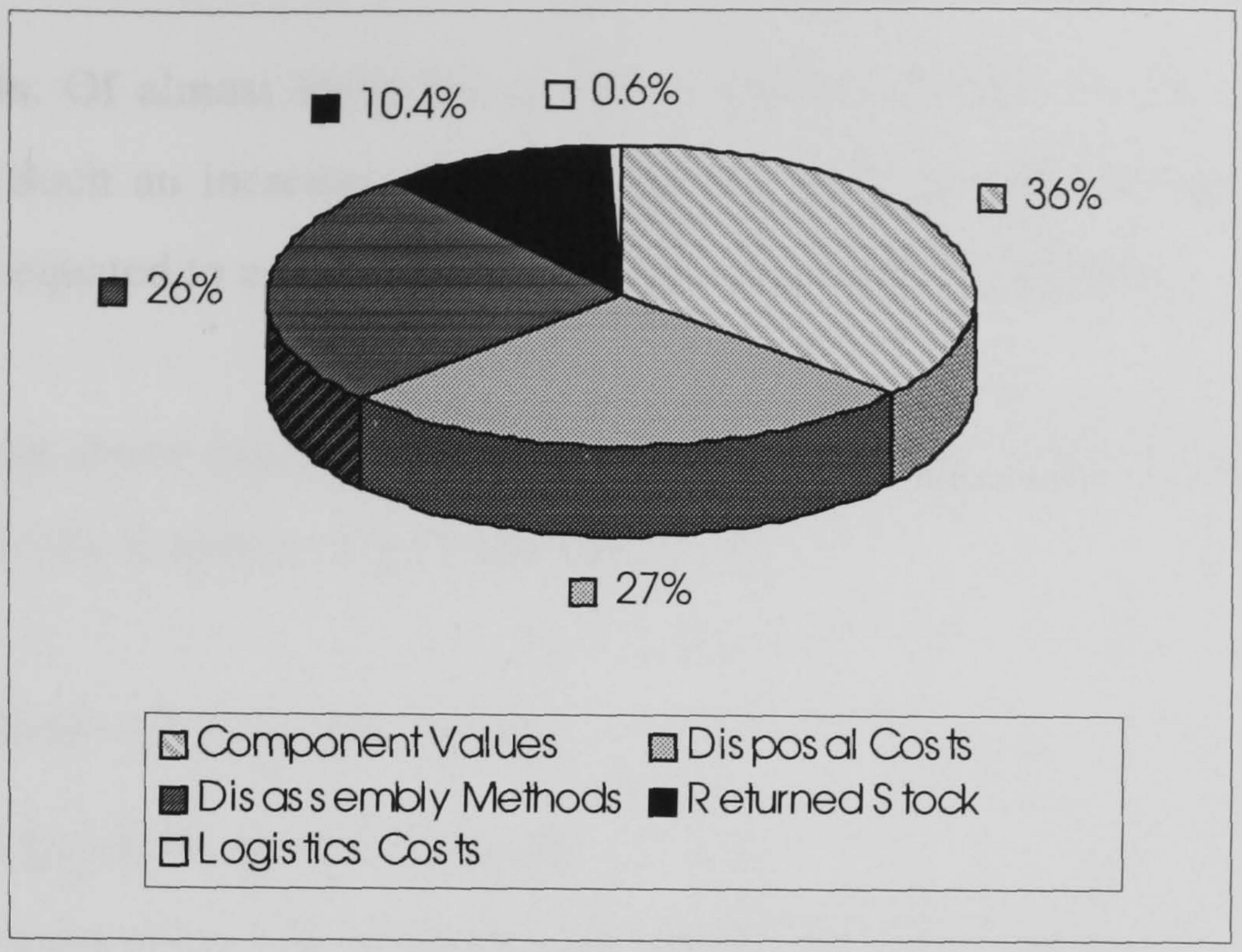

Figure 8.3: Variability of external influences on the product

Component Values. The greatest area of concern was in the value obtained for materials and more importantly components which have a high value because of their importance in the service function. Additionally the cost of refurbishing these components was low because of the existing take back facilities that the company already have in place. The variation in value of EOL components could alter the product's profitability by 36%.

Disposal Costs. The next area for concern was the imposition of a landfill levy. As a starting point a levy, ranging from £0 to £2 was assumed for each product entering a landfill. The resultant contribution to the overall variability was 25.8%.

Disassembly Methods. An increase in the efficiency of disassembly was the next area of concern. If it is assumed the disassembly time is improved by 50% as a result of automation (semi or otherwise), then the contribution to variability is 25.1%.

Returned Stock. Return rates of between 4% and 14% were less important, giving a variability of 14.3%.

Logistics Costs. Of almost insignificant effect was an increase in the return logistics costs of 15%. Such an increase could realistically occur as part of legislation against pollution. This equated to a contribution of 0.04% to overall variability.

In addition to the above experimentation, best and worse case scenarios were conducted with the model. The findings are given below.

Best Case. The best case scenario, where:

- 14% of the products were returned
- the components and materials realised the highest possible values
- the logistics costs remained at current rates
- there was no landfill levy
- the labour cost was halved due to the investment of automated disassembly methods and tools.

resulted in an additional annual profit of **£0.375 million** for the product. This assumed that 31% of the raw material value could be refurbished as whole components for inclusion in service repairs, assuming that legal requirements are met.

Worst Case. The worst-case scenario, where:

- only a small percentage of products (taken as 4%) were returned
- the logistics costs rose by 15%
- a landfill levy was imposed on 80% of the 96 % of products that ended up in landfill sites
- the components had no service demand and only the lowest material scrap value
- all material reclaimed was sold to scrap re-processors for the lowest prices
- the labour cost remained the same.

resulted in an annual loss of **£0.3 million**.

The application of AMDEL was undertaken in the main by the team from Cranfield University. This worked well because the team from Cranfield had previous experience and skills in computer simulation modelling and applying the mathematics of ANOVA, whilst the company did not. The next stage of AMDEL was for the company to analyse the findings and decide upon a set of actions. Representatives from the company were given feedback on the results.

Based on the analysis the company team felt that it was essential to reduce the variability of the material and component values in the product. This was clearly demonstrated by the 36% contribution to variability. One of the prime causes of this variability was due to a lack of certainty over the demand for refurbished EOL components in the service function. Therefore the company concluded that of key importance was the need to ensure that the service function used as many refurbished components as possible. However, the demand is regulated by the reliability of products in the field. Hence, the company was presented with a dilemma, by increasing the reliability of their products and customer satisfaction, they would reduce the EOL profitability. As a result, the company conducted further work to examine whether the components from its product could be used in the service of other similar products.

Furthermore, the company felt that the variability could be greatly reduced by introducing refurbished or remanufactured components into newly manufactured products. However, there are many problems with this philosophy, for instance, with legal, safety and reliability, why used components should not be utilised in some new products. The company decided that they could not risk their reputation and thus their market share by introducing used components into new products with the inherent danger of their failure, resulting in a premature or unreliable product life.

A small landfill levy indicated that even a small levy represents a large risk, in this case a 25.8% contribution to variability. However, because it is outside the control of the company little action can be taken. Lobbying of Government, through an industry forum was the only action considered possible by the company.

Finally, the company considered the variability of the return rate of EOL products, which contributed to 14.3% of overall variability. The company decided that a scheme offering existing customers incentives to replace their old product with a new product at a competitive rate could be favourable. However, there were concerns that there might be an over supply of components for the service function.

8.3 Case Study Conclusion

In modelling the life cycle of the product range it was shown that the potential additional contribution to profitability of the single product range by taking back EOL machines could be £0.375 million per annum. However, the analysis also demonstrated that due to a number of uncertainties, the taking back of the product range could cost the company £0.3 million per annum.

The case study highlighted that the area of key concern was the demand for components in the service function. With the time constraints of the research, the case study concluded at this point. However, it demonstrated the way in which AMDEL can be used to focus on the key variables which contribute the most to economic variability and in this case potential financial loss.

The reaction of the company towards AMDEL was extremely positive. This was most obviously demonstrated in the effort to collate additional data, produce further models and conduct analysis. It provided the design team with a structured way of working, providing the design team with a methodology in which reasoned analysis could be undertaken and debated. They have now focused on commonality of service items across their range of products, developed further models in order to apply AMDEL across a range of their products and more importantly are focusing upon the design of new products having recognised the profits that could be achieved through product take back.

The above reaction from the company demonstrates that AMDEL is usable; that it is easily understood by design teams; that it is effective and finally that it works, so providing confidence to other potential users.

8.4 Conclusion

Within the case study, the use of AMDEL provided the company with a means of evaluating the economic impact of taking back products at the EOL. The findings identified the area of greatest variability in the profitability to be the demand for components in the service function. The company involved in the case study can now choose to avoid or diminish this variability. One further option which is being evaluated is whether refurbished components could be used in new product manufacture for example, (providing all legal and marketing responsibilities were satisfied), then the problems with the possible lack of demand and its associated uncertainty could be eliminated. Obviously, this could vastly increase the profitability, providing that future designs take account of past model component usage.

Through the use of an industrial case study, this chapter has shown that AMDEL meets the last two of the five requirements set out in chapter 4; that a new methodology must:

- be usable and the results easily understood by design teams
- provide confidence that it works.

With the time constraints and the aim of validating the methodology with regard to its comprehension by a design team, the case study did not look at alternative designs, materials, the avoidance of composites, new fastening methods or the re-designed product and its reduction in cost and improvement in performance. The case study was limited to a single existing product range. Typically, a re-designed product should be subject to the same analysis to ensure that the changes in the design are an improvement, often changes in one area of a product design have unforeseen impacts in another area. Such analysis should include, for example as AMDEL does, increased sales volumes due to the expected increase in sales that tend to follow a design improvement.

9. Conclusion

9.1 Discussion

Material resources are becoming evermore scarce, as demonstrated in chapter 2 by Table 2.1. The estimated lifetimes of global resources are such that even at current consumption rates and with increased extraction technology, the supply of natural resources is limited in many cases to no more than 300 years. Obviously, future technology advances will probably ensure the use of less natural resource in the production of new products. However, EOL product take back by the original manufacturers and recycling is viewed as an important process in helping to address this problem. The initial research by the author, outlined in section 1.2, identified that legislation is moving towards making manufacturers responsible for their products at the end of the product's life.

Once a product has been established within the market place, a company cannot change the structure of the product in the field or escape its legal liability if take back legislation is introduced. However, it is probable that any such legislation would be selective in its approach to dealing with products that are already in the field, allowing companies time to plan the EOL for future products. The introduction of completely retrospective legislation would have the potential to bankrupt whole industries.

In section 2.8, it is argued that impending legislation should be treated as an opportunity and not a threat. The idea of value added in manufacturing being reclaimed in the form of components and materials at EOL and used in the next generation of products is gaining in popularity. The section introduced case studies from three main industry sectors which were identified as being the first that will experience EOL product take back legislation: automotive, computer and electrical goods. It was shown that even without legislation, some companies or third parties already take back EOL products for profitability reasons alone. In some cases, as described in section 2.9, products that have reached EOL in the UK are despatched for secondary markets in developing countries. For instance, the design life of a telephone is on average 18 years, where in practice it is replaced on average after only 18 months in the UK. This has seen the establishment of an export business which sells some 20,000 phones per month to Poland. Hence, for products which still have a functional life, at an EOL dictated by consumer tastes, it may be economically and environmentally sound to export such products to emerging countries for further use. In developing countries the scarcity and cost of landfill is generally not a problem, however such a policy of disposal may be environmentally damaging. For example, the tritium gas contained within the dials of old Trimphone telephones produced a luminescent glow, allowing the dials to be identified in the dark. However, there is no safe disposal route for such materials and in the UK these EOL telephones have to be held in a licensed storage facility. In section 2.3, the issue of refurbishment was discussed. Some products, such as the London Routemaster bus are regularly refurbished in order to extend their life and avoid the high capital cost of replacement. However, such buses are not as environmentally friendly as their latest generation counterparts in terms of vehicle emissions. Hence, although some recycling concepts seem economically advantageous, it does not necessarily follow that they are environmentally sound.

It was discovered that historically the domestic white goods sector has little experience of product take back. Although refrigerators have to be taken back at EOL, in order that their coolant is removed under controlled conditions, to ensure that CFC gases are not released into the environment, they are currently dealt with by local authority disposal sites and not by the manufacturers. Hence, companies in this sector are poorly prepared for the impending legislation and therefore this sector formed the focus of the research.

The initial research by the author, outlined in section 1.2, identified that there is little consideration within the design process of the economic implications of product take back. However, as is discussed in section 2.10, the greatest opportunity to influence the impact and hence life cycle profitability of a product is at the early design stages. For design teams this raises an additional and difficult demand to their existing scope of responsibility. Typically, as outlined in section 2.11.1, a design team consists of designers and individuals from all other related functional areas of the product design. There have been many implementations and much research work on design methodologies for a number of perspectives within the life cycle of a product. They typically involve collecting data from many sources, such as the outline design, tool design and production methods, and presenting the results in a format whereby the impact of a design decision can be evaluated by a design team. As described in section 8.2.2, given an infinite amount of time a design team could design a perfect product. However, there is a point at which a trade off has to be made and the proposed design signed off, because the consumer will not wait an infinite amount of time. Hence, design methodologies provide decision support to design teams in order to make design decisions that ensure that the value achieved in improving a design does not exceed the cost expended.

In the product take back domain there are a lack of design methodologies. The more proactive organisations, typified by BMW, have begun analysing product designs to improve the amount of recycled material used in the construction of the car and also to improve the dismantling and recycling of materials at the end of the cars life. However, such analysis relies upon experienced designers and engineers reviewing designs and proposing changes. The company has produced some generic guidelines that make disassembly simpler. These comprise of obvious qualitative information, such that glue and rivets are undesirable for disassembly. The more successful design methodologies, as discussed in section 2.11, used in areas of the life cycle, such as manufacture and assembly provide quantitative advice, which is in the form of scoring and cost systems.

Companies should consider whether they even need to take product back at EOL. For instance, if there is no legislation requiring take back and the nature of the product deems it unsuitable to take back, then the need to consider the EOL may be non existent. Section 7.1.1 introduced the concept of a check list that a company should follow, in order to examine the need to consider EOL.

If EOL product take back is potentially desirable, then the design team will be concerned as to how they ensure that the next product that they design will be cost effective to take back. No existing tools were found that met this new challenge facing design teams. Furthermore, the use of current costs to consider the EOL scenario is a potential hazard because the future involves uncertainty about events and values. Therefore it was shown that design teams require a decision support methodology that provides a life cycle economic view of the product design, taking into account uncertainty involved in dealing with the future, to create economically superior products, that comply with or surpass environmental legislation.

In chapter 3, the research found that Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) were methodologies that were found to have been valuable in evaluating and providing decision support on the implications of life cycle design concepts. In practice, LCA has addressed broad environmental impacts, but has had few applications to real business decisions. LCC has been used by the military and construction industries for a number of years. However, LCC has seldom included environmental legislative, disposal or product take back costs. Despite this limitation, the research discovered that the principles of LCC could be used to form the basis of an economic life cycle model.

Section 5.3 described how LCC allows cash flows from different product life cycle concepts to be expressed in a common unit, as though the individual cash flows occurred at the same point in time, in order to provide a fair comparison. Discounting of the cash flows uses the interest rate as an implicit time value of money and allows a comparison to be made. However, in periods of low inflation, costs and revenues equally inflate with time and tend to cancel the effect of the other, providing a real difference of only 2 to 3 percent. A further detailed explanation of the time value of money is given in Appendix C.

Chapter 4 provided an example of how by designing for EOL product take back a company could make a profit. However, the example demonstrated the effect of uncertainty with the reliance upon estimates and assumptions. For example, in the simplified chair example no account is made for overhead recovery. The method of apportionment of such overheads could alter the outcome of the analysis. For instance, returned products could avoid the potential high overheads of the manufacturing company by being subcontracted to a third party. In addition, there is a risk that by deferring some of the profitability to the future, by designing products which are expensive to manufacture yet offer a greater return at EOL, the company may incur financial hardship and cease to exist. The value built into products could then be claimed by another company who chooses to take back the products at EOL. The chair example illustrates the need to consider all elements of a product's life to properly assess the economics of the life cycle. However, it also demonstrates some of the problems when trying to apportion costs and make assumptions concerning the future. Appendix F examines the issue of costing systems in more detail.

Section 3.4 examined the many causes of life cycle uncertainty. Consumer behaviour will change, not just at the point of purchase but through use and into disposal. Consumers may feel socially responsible to return EOL products to designated disposal points. Certainly the infrastructure for waste management, already moving from a cottage industry towards recycling factories, will change. The value of today's components and raw materials will change, with new markets opening up and old ones disappearing. Labour costs will change and the technology used for waste management will change dramatically. Technology may advance to the point where robots are able to disassemble products.

Some of the uncertainty surrounding the product life cycle can be controlled to a degree. The company can control the return rate by varying the amount owners of EOL products receive if they return the products. However, with some of the uncertainty, a company has no influence. Such uncertainty can be of two types, the first is continually increasing or decreasing over time, the variation for instance, in external scrap metal markets. The second type of variation is that which is binary, it either occurs or it does not. For example, the introduction of legislation, consumer behaviour or the establishment of a recycling infrastructure. The level of control a company has over such variables still does not allow the company to predict future actions with confidence. Therefore we can expect the language of uncertainty to become more common as designers seek ways to cope with this challenge.

Uncertainty in the past has been dealt with by the application of risk analysis, as detailed in section 3.5. Risk analysis can be defined as the conversion of the elements of uncertainty into elements of risk through the allocation of a probability distribution. Risk therefore becomes objectively measurable and uncertainty something that is perceptual in nature and human centred. However, the research identified that methods which incorporate uncertainty through statistical techniques have resulted in output which is oversimplified and deficient to decision makers. The hazard of such techniques is not that they will be wrong, but that they will be accepted literally and that an illusion of knowledge will develop. The research identified ANOVA, with its application of robust design principles, as an alternative approach to risk analysis. Such a technique is an accepted method of dealing with uncertainty, particularly within the manufacturing domain. For instance, a model of a manufacturing system is developed and subjected to a set of experiments defined by ANOVA. The results are analysed, the output of which provides guidance on the source of variations in performance. Based upon this information, a manufacturing system can be re-designed to ensure that it is robust to the occurrence of future events. As an alternative to ANOVA, an approach known as Liner Approximation was identified and examined, with the two techniques compared in chapter 6. The results demonstrated that while both techniques met some of the requirements of a new methodology outlined in section 4.5, ANOVA is the most suitable due to its practical applicability.

Historically, companies have based product design decisions on the basis of economics. They understand the language of money, it is a common language across all company disciplines. The research found that the more proactive companies who have implemented product take back schemes have done so, not through environmental principles, but because it is profitable. These companies tend to select only those products that are profitable to take back, leaving the non-profitable products to be disposed of through existing disposal routes. However, with impending legislation companies may be compelled to take back all EOL products. Therefore increasing emphasis will be given to designing products with life cycles that are profitable. The research demonstrated that the element of uncertainty introduced by considering environmental issues and the complete economic product life cycle complicates the design decision making process. It is not feasible to assign values to the later stages of the life cycle with any certainty, for example, the reclaimed material value achieved ten years in the future may be very different to the reclaimed value to that of material today. Therefore design teams are faced by an increasing responsibility to produce cost effective products, yet lack the tools to help make superior product design decisions.

9.2 Conclusions

Design of products is a complex process. For example, products with hundreds of parts, dozens of materials, thousands of consumers, multiple sales routes etc., demands a high degree of support. The introduction of EOL legislation creates new problems which require a new type of support. The AMDEL methodology is designed to meet this industrial need and is divided into three distinct and iterative stages - definition; model generation; and experimentation and analysis. By taking a structured approach the methodology is sub-divided into manageable stages, reflecting best practice in problem solving. The methodology promotes both effectiveness and efficiency by focusing initially on a high level of abstraction, as is often found with the initial conceptual design phase, before directing the detailed effort of the design team on those areas which are most important in addressing economic uncertainty as the design progresses.

However, prior to the application of AMDEL, a company should question whether their products or their industry are likely to be subject to product take back. For example, as described in section 9.1, if there is no impending take back legislation, short product lives with rapidly advancing technology and low production costs, then the case for taking back products will be virtually non-existent. In such a scenario, a company should take a longer perspective and ask itself the type of questions set out in section 7.1.1. If it is obvious that take back will not occur, then the company may pursue the optimisation of production, using such fastening techniques such as glue, which render disassembly difficult.

Existing design methodologies provide design advice in two ways, either qualitatively or quantitatively. The research discovered that existing qualitative methods typically provide general advice on best practice for a particular life cycle perspective. However, in considering the entire product life, a form of quantitative metrics allow the design team to resolve trade offs. The AMDEL methodology generates quantitative numeric outputs on cost and contribution to variance which can be easily understood and compared by design teams. The metrics indicate to the design team the contribution of different variables to the overall variability of the product's economic life cycle. Such metrics facilitate multi-disciplinary debate, design trade off decisions or further design innovation [Boothroyd 1994]. The methodology is used to identify the largest concerns on the initial data gathered and so help focus effort on collecting further data. It is applied in an iterative manner to new designs encouraging improvement and guiding the design process to creating both product and component life cycles that are economically robust.

At the centre of the AMDEL methodology is a computer simulation model, which represents the economics of the product life cycle. The model ultimately comprises of a vast amount of data which has to be modelled. The manual simulation of such large amounts of data in the current age of computer tools is not acceptable. Hence, in order to allow the efficient use of AMDEL it is appropriate to adopt some form of computer aided assistance. This at its most simple can be in the form of spreadsheets and at its most sophisticated in the form of discrete event simulation. Spreadsheets have the advantage of requiring a low degree of expertise to establish and are in-expensive. However, the output of data can be difficult to interpret and the model can be difficult to manage as its complexity increases. Computer simulation on the other hand is time consuming and expensive. However, the research demonstrated that use of such a discrete event simulation package allows the model to be built and that the use of animation provides confidence that the model is performing correctly.

The utilisation of the model linked to ANOVA was shown to be practicable and guide the analysis process in dealing with the life cycle uncertainty. Section 7.1.3 described how ANOVA dictates structured experimentation can be undertaken using orthogonal arrays. Depending upon the number of variables identified from the definition stage of the methodology, a process outlined in section 7.1.1, a standard orthogonal array has to be selected based upon the criteria set out in Appendix E. Following the selection of the array a simulation model is constructed, experimentation undertaken and analysis of the results performed. During the case study, the generation of the model was the most time consuming factor and is described in section 8.2.2, taking some 40 man days, mainly due to validation of assumptions.

The industrial case study, described in chapter 8, demonstrated that AMDEL provides a decision support method that influences the design of product life cycles to produce economically superior products within the domestic white goods sector. The study further demonstrated that such a methodology is possible to construct, is practicable and beneficial. A major finding of the case study was that by applying the AMDEL model to an existing product range, the company could by taking its products back at EOL make a substantial profit. In addition, the analysis also demonstrated the importance of strategically planning for the use of existing components in the design of new products. The company found that the methodology was accepted and understood by the design team. As a result the use of the methodology continues to be applied on new product ranges.

Although successful in its application in the case study, the AMDEL methodology was only partially validated, as described in 8.1, due to time constraints and the need to validate the methodology with regard to its comprehension by a design team. Therefore the methodology was applied to one company on an existing product range and only for a retrospective "value engineering" re-design exercise rather than for a new product design. The case study did not investigate alternative designs, materials, the avoidance of composites, new fastening methods or the re-designed product and its reduction in cost and improvement in performance. Typically, a re-designed product should be subject to the same analysis to ensure that the changes in the design are an improvement. Such analysis should include, for example as AMDEL does, increased sales volumes that tend to follow a design improvement and the impact such volume increases would have on the choice of disassembly technology.

The case study did not examine the application of AMDEL within the new product development process and how it might be used to compare design alternatives and generate debate within the design team. Within the case study, some debate was generated about future product design. For example, as described in Appendix H, an area of debate was the positioning of the motor in the machine. Some of the design team argued that with the motor at the top of the machine, serviceability was easier and life-span increased due to the drier conditions at the top of the machine. In addition, less expensive electrical wiring was required. On the other hand, there were arguments for the motor being at the base of the machine based on increased stability and hence better operational performance in terms of vibration. Placing the motor at the base of the machine would ensure that manual recovery of the motor at EOL would be difficult. Given that the motor has the highest value, then the two motor positioning alternatives would benefit from careful analysis using AMDEL. The resulting output may lead to the generation by the design teams of further design alternatives or radical solutions. For example, EOL volumes may be high enough to justify the development of robotic disassembly technology that ensures the motor can be removed cost effectively from the base of the machine.

The case study undertook costing of the take back process using figures allocated by a cost accountant. However, a potential problem would be the way in which costing of EOL take back revenue would be included in company accounts. A review of costing systems is given in Appendix F. The Statement of Standard Accounting Practice on Stocks and Work in Progress published by the Accounting Standards Committee does not provide guidance on the accounting of product take back at EOL, however, they give advice on long term contracts, which are similar to take back where a future action will involve cost to realise a profit. This states that in the case of cash flows associated with a long term contract, where "their outcome can be assessed with reasonable certainty before their conclusion, the attributable profit should be calculated on a prudent basis and included in the accounts for the period under review". The problem associated with EOL take back is that a degree of uncertainty will always remain. The problem is exacerbated if a product range in a particular year has had value invested in it in order to improve the efficiency and profitability of take back. In that financial year, manufacturing costs would be increased and hence profitability potentially reduced. Hence, the company accountant would be faced with the task of trying to justify this increased cost against an asset that could be realised when the product is taken back in future years. The accountant could perhaps not place reasonable certainty on this value being realised and hence not account for it in the financial figures. The result would nullify any argument for considering EOL take back, even though it may in the long term be more profitable. However, take back legislation could require that EOL products are the responsibility of the manufacturer. Such legislation would then result in products that are in the field being considered a liability, in the same way that the Trimphone telephone has become, as detailed in sections 2.9 and 9.1. The whole issue of how accounting practices deal with EOL could effect the viability of product take back and is an area that requires further investigation, as discussed in section 9.3.

In conclusion this research has shown that:

- The domestic white goods industry has little experience of dealing with EOL products
- Companies can make a substantial profit from taking back EOL products
- Companies need to consider the reuse of existing components in new products
- With the advent of EOL take back legislation design teams require a new form of decision support
- The new form of support must consider the whole product life, economics and uncertainty
- The language of money is a useful common language which can assist trade off between company disciplines
- Design teams prefer design decision support methodologies with metrics when making trade offs
- It is possible to combine the existing tools of LCC, simulation and ANOVA in a new and integrated methodology to successfully support the creation of economically superior products.

9.3 Further Work

Throughout the research a number of observations were made and these form the basis for several areas of recommendations for further work.

9.3.1 Testing

It was identified in section 1.2 that the automotive, electronics and domestic white goods markets will be among the first industries to experience EOL take back legislation. Hence, these industries potentially will require support in the form of methodologies such as AMDEL. The domestic white goods industry was identified as the industry that was least prepared and therefore the case study focused upon a single company within this industry.

In applying AMDEL retrospectively to a single product range, the main aim of the research was only partially met. The case study was limited to a single existing product range . The study did not consider alternative designs, materials, fastening methods or the re-designed product and its reduction in cost and improvement in performance. A re-designed product should be subject to the same analysis to ensure that the changes in the design are an improvement. Changes in one area of a product design could have unforeseen impacts in another area. Such analysis should include, for example as AMDEL does, changes in volumes that tend to follow a design modification.

There is a need to undertake a detailed test programme for the methodology in a wider range of companies and across a range of industries. The programme should aim to demonstrate superior results through the use of AMDEL on a new product design, identify particular industries where the application of AMDEL is not suitable and show that the use of AMDEL retrospectively within other industries is feasible.

The methodology was only applied retrospectively to an existing product range. The next stage would be to test the methodology with the design of a complete new product range within the domestic goods market. With product development in the domestic goods industry being in the order of years, considerable time would be required working with a company to demonstrate the benefits of AMDEL. An alternative, if time is a constraint, would be to apply AMDEL to a component design, however, one should consider that by optimising a single component, the overall product design may be compromised. The demonstration that AMDEL has produced a superior design, compared to the design that would have been produced without the use of AMDEL is subjective, unless the test isolates two identically capable design teams and allows one of the teams to use AMDEL and compares the resulting product designs over their life cycle. It is only once a product range has been subject to its entire life cycle through to EOL that it can be shown that through the use of AMDEL that it was economically superior.

Whilst AMDEL is being tested within the domestic white goods industry, it could also be applied to other industries and in particular, the automotive and electrical industries. It was identified in section 1.2 that these industries will be among the first industries to be subjected to EOL product take back.

Obviously, the case study demonstrated the suitability of the methodology being applied retrospectively and therefore it is also necessary to undertake such testing in other industries. Such testing, which can be undertaken over a short period of time, compared with the long term testing of the methodology against a new product design, demonstrates that the methodology is usable and the results easily understood by design teams and provides confidence that it works.

9.3.2 Take Back Legislation

The impact of EOL product take back will to some extent be driven by product take back legislation. The majority of such legislation originates from the EU and there is uncertainty, as described in section 4.5, on the potential impact for particular industries, especially as proposed forms of legislation are frequently changed. For example, will import restrictions be imposed for products that do not meet green criteria; will companies have to retrieve EOL products back to their country of origin; will they be offered grants to establish take back facilities in foreign markets and therefore reduce the inevitable pollution created by inter continental reverse logistics routes; which countries are planning selective legislation and which are planning retrospective legislation in its approach to dealing with products that are already in the field, allowing companies time to plan the EOL for future products? Companies require a regularly updated database or electronic information feed which provides accurate information and helps to reduce uncertainty.

9.3.3 Costing Systems

It was identified in section 4.3.2 and Appendix F that current costing systems do not have experience of dealing with costing EOL take back strategies. Such costing systems have the potential to discourage EOL product take back by not recognising the extra cost that may be required to be built into a product during manufacture in order to increase the yields of EOL product take back yield. Further work is required to examine how costing systems could represent EOL take back strategies in a fair manner.

9.3.4 Environmental Costs

Observations made during the course of the research has shown that companies understand the language of money, thus an economic model of environmentally related product strategies can increase understanding and motivation within the company to create environmentally superior products and strategies. Therefore if the AMDEL methodology is to encompass a measure of environmental value, then a process of assigning economic cost to environmental bad practice is a major area for further work. For example, the environmental cost to society of emissions created by using lorries to return EOL products should be weighed against the value to the company. Without such figures companies find it extremely difficult to make valued decisions.

9.3.5 Product Data Management

The work concerned with the case study identified that a potential problem in product take back was understanding the type of use that products have received throughout their life and their exact configuration and composition. Some machines, which although aesthetically seem to be in a pristine condition, have in fact been subject to heavy usage which reduces the value of components for re-use or refurbishment. Some automotive manufacturers already fit "usage chips" to cars in order to determine the service intervals and to perform diagnostic analysis. Additionally, products may be taken back 30 years into the future. Product ranges are often subject to upgrades, changes in specification and configuration. For example, a component using a high value material may have been replaced at a certain point with a cheap substitute. In such a case, the argument for disassembly may depend on whether the product contains the high value component. Hence, an area of further work required is that of 'green chips' or 'milometer chips' which log information such as the amount of times a machine/component has been used; and importantly the bill of material.

In addition to storing information concerning the products life and configuration and specification in the product itself, it is also important to understand the methods used in production and provide instructions on disassembly. Some companies have established product data management systems, which provide an information repository of data concerning product design, productions and service. The US led CALS (Computer Aided Life Cycle Support) initiative has defined standards for such product data management.

Hence, if products are returned at EOL to the manufacturer who has no knowledge of the use, specification, configuration or methods for dis-assembly, then the value of those EOL products are diminished.

9.3.6 Product Tracking Systems

In order to assist in the return of products at EOL, companies must have knowledge of the location of their products. Consumers may through advertising and product literature issued at the point of sale know that an incentive can be collected if they return the product at EOL to the manufacturer. However, if products are passed on in secondary markets to new unknown owners, perhaps in other countries as described in section 2.9 then the return of EOL products will be difficult. One method of tracking products and ensuring their return is through product leasing, as described in sections 2.8.3 and 2.9. The manufacturer retains ownership of the product which has to be returned at the completion of the lease period or when an upgraded product is substituted during the lease period. Through initial warranties companies may know the identity of the original owner, but again this information is often lost when a product is sold on. Hence, in order to facilitate take back at EOL tracking systems are required, in order for the company to know who owns its products and the probability of the future potential supply of EOL products.

9.3.7 Disassembly Decision Support

During the case study, which is further described in Appendix H, it was identified that the AMDEL computer model had the potential to be used as a daily decision support tool. It modelled the individual disassembly operations; the cost of the operations; the value of any scrap; the cost of refurbishment; and the value of the refurbished component. A graphical plot was made of the cost expended and the value recovered as the machine was disassembled, demonstrating the profitability. By varying the values, costs and precedence of disassembly, different profit profiles can be established. Information could be provided from external and internal sources relating to the current service demand for components and the current prices for scrap material. Hence, the disassembly operation could be optimally managed on a real time basis. If there is no future demand for say a particular motor in a washing machine in a service application, then it would be of little use in extracting the motor, disassembling and refurbishing that motor. If the scrap cost was less than the extraction cost, then it would make economic sense to leave the motor in the machine and send the whole machine to a scrap reprocessor or landfill site dependant upon the values and penalties that would be achieved or incurred. It is critical that demand for components is planned accurately. In the case study, the key to profitability was the ability to use the motor in service applications.

Therefore, a decision support tool is required to provide real time advice to assist in the optimal daily operation of product take back facilities.

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APPENDIX A

Concurrent Engineering Case Studies

One of the distinctive characteristics of World War II weapon design was the reduced time to market achieved by civilian design teams. One of the most early examples of this was the P-51 Mustang fighter aircraft produced by the North American Aviation Corporation. In May 1940 the company received a British order for 320 P-51s, with the condition that the first prototype had to be ready for flight test within 120 days. The British provided the company with a set of specifications and a three dimensional drawing of the aircraft. Given this seemingly impossible task, it might be assumed that the multi-disciplinary design team of 97 engineers and technicians would have used evolutionary design concepts from previous designs. Instead the aircraft incorporated many novel features, including laminar flow airfoils and the introduction of a combined radiator housing-ejector nozzle that provided 300 pounds of jet thrust, instead of the usual radiator drag. Even more remarkable was that the prototype was completed in 102 days. Later the British installed a Rolls Royce Merlin engine, the same as that installed in the Spitfire. In comparison, the US Mustang had a higher rate of roll, 50 mph greater top speed and had a much longer range, despite being 1600 pounds heavier. In addition, the Spitfire was designed with aerodynamic performance and structural efficiency as the main considerations, to the detriment of production [Gruenhagen 1976]. The Spitfires elliptical wings were extremely difficult to produce, with over 13,000 hours require to build a complete aircraft. In comparison, the German ME-109 fighter, which had a similar performance envelope of the Spitfire, took only 4000 hours to produce [Evans, D. 1992].

Another often quoted examples of early CE practice is that of the Lockheed Aircraft Corporation's Skunk Works. The Skunk Works were established in 1943 in Burbank, California by Kelly Johnson, a leading design engineer to develop the first mass-produced US jet fighter plane, known as the P-80 Shooting Star. The aim of the project was to produce an airworthy prototype in 180 days. To achieve this Johnson established a small integrated, multi-disciplinary design team, with 23 engineers and 103 manufacturing engineers. The project was complicated by the aerodynamic advances needed to produce the fastest plane to date and the incorporation of jet propulsion. Despite this the prototype was produced in 143 days, 37 days ahead of schedule. In later years several other projects were completed by the Skunk Works and these included the U-2 spy plane which was conceived, built and flown in 8 months, within budget. The success of such programs was attributed to the formation of integrated design teams which featured selected design and manufacture personnel, who worked with clear specifications, an adequate budget and no external interference [Rich 1991].

Despite the success achieved through the use of wartime Concurrent Engineering design teams, the CE concept virtually disappeared until the 1970's. Until this period the design and development of new cars was sequential, undertaken in a series of ordered, unrelated, and uncoordinated steps by people in isolation from one another in different departments. In addition each departmental specialisation was autonomous, with its own goals and no common company goal. It was during 1979 that Ford initiated a project to produce a car with the quality of Japanese and European imports. Such imports had devastated much of the existing US car industry, with customer focused designs and high reliability. The project was undertaken on two Ford models, the Taurus and the Mercury Sable. At the heart of the project was the use of cohesive multi-disciplinary teams consisting of personnel from areas such as product planning, marketing research, design engineering, manufacturing, logistics, and finance. Production workers from the shop floor were involved in the design process to advise on possible production problems with proposed product designs. Further input was gained from potential customers and suppliers of the Tarus. The results of the project exceeded the expectations, with the Tarus winning accolades as one of the world's best ten cars in 1986, 1987 and 1988. In 1988 a market survey revealed that 91% of customers would buy another Tarus and 94% another Ford [Doody and Bingaman 1988].

The US Department of Defense (DoD) has promoted and implemented CE within weapon system production and in 1988, the Defense Advanced Research Projects Agency (DARPA) launched the DARPA Initiative on Concurrent Engineering (DICE) to encourage the practice of CE in the US military and industrial base.

Other organisations implementing CE in the US include Hewlett-Packard, AT&T, Texas Instruments, IBM, and Chrysler [Jo, Parsaei and Sullivan 1993]. Through the application of CE principles Siemens Automotive have realised improvements in both productivity and quality. In 1975 Siemens produced 30,000 fuel injectors a month. In 1991, the company manufactured 30,000 fuel injectors a day with defect levels of 20 parts per million (0.002%). In addition through the collaboration of designers and process engineers, the number of process grinding steps were reduced six fold. Over that same period, the direct human labour required for each fuel injector was reduced from 13 minutes to less than 2 minutes.

Historically, Motorola the telecommunications company required 30 days to build a telephone pager [Eagan 1994]. By implementing cross-functional design techniques and introducing significant levels of automation, a single pager can now be manufactured in 30 minutes [PBS 1991]. New engineering employees at Motorola now undergo a 24 week Concurrent Engineering Training Program, before they take up their position [Jo, Parsaei and Sullivan 1993].

Through the use of CE, Japanese car producers develop a new model on average in a third of the time and with 50% fewer engineering hours than North American rivals [Jones 1992]. Moreover, the quality of their designs, as indicated by the design's manufacturability is distinctly superior [Womack et al. 1990]. This superior performance in product development has allowed Japanese automotive companies to construct a completely new product strategy. During the 1980s, they doubled the number of products in the market place, whereas European companies rationalised product ranges. In addition, they achieved this while still retaining a four year product model range replacement cycle, rather than the eight to ten year cycle common in western markets. They are now concentrating on market niches and designing vehicles which they can sell on product attributes rather than price. More recently they have moved into the luxury car market, with models such as the Toyota Lexus, giving companies such as Porsche and Mercedes an unpleasant shock. The faster replacement cycles allow Japanese companies to incorporate changing tastes and new technologies ahead of western competition, therefore gaining market share from western car companies. This strategy has been seen to such devastating effect in the camera, consumer electronic and motorcycle industries.

Japanese design activities are based around individual projects and not traditional functional departments. Each project has a team of specialists from each function for the duration of the project. The members of the team work closely together, drawing on the services from the different functional departments. The team looks at the precise cost of each part and uses value engineering techniques to analyse the "trade off" necessary to meet the target price. Traditional product development typically involves design departments producing an ideal component, with manufacturing informing the project manager that it cannot be made for the target price. A political bargaining process then begins between departments until a compromise is reached. This costs valuable time and hence results in the product being late to market and often troublesome to manufacture and operate. However, by adopting a team based approach conflicts are identified and "trade off" made early on, with the result that the product is much easier to make and operate and reaches the market ahead of competitor products [Jones 1992; Twigg and Voss 1992].

APPENDIX B

The History of Life Cycle Costing

It was in the late 1960's that the term life cycle costing was established in a report entitled "Life Cycle Costing in Equipment Procurement", which was the result of a study by the Logistics Management Institute for the US Assistant Secretary of Defense for Installations and Logistics [LMI 1965]. The reason for this study was the principle that US defence equipment must be supported over its life cycle in order to ensure operational effectiveness [Fabrycky and Blanchard 1991]. Depending on the equipment type, the support costs can be between 10 and 100 times the acquisition cost. As a result, a series of three guidelines were published by the US Department of Defense concerning life cycle costing followed by the Directive 5000.1 entitled Acquisition of Major Defense Systems in 1971 [DoD 1971].

In 1974, the State of Florida formally adopted life cycle costing as part of its procurement process and in 1978, the US Congress established the National Energy Conservation Policy Act, which requires every new federal building to be life cycle cost effective. Since this date, many other states in the US have passed legislation making life cycle mandatory in the planning, design and construction of state buildings.

Dhillion provides a review of numerous articles on the application of Life Cycle Costing in the US and the UK concerning the defence industry [Dhillion 1989] while others provide a review of work undertaken in the construction industry [Flanagan et al. 1989; Bull 1993].

Dhillion has identified a number of cost models which consider EOL [Dhillion 1989].

Model VII

This model is applicable to the domain of full product life cycle including product take back. The model has four major life cycle cost components: research and development cost; production and construction cost; operation and support cost; and retirement and disposal cost.

Mathematically the life cycle cost is given by:

$$LCC = RDC + PCC + OSC + RADC$$

where,

RDC is the research and development cost
PCC is the production and construction cost
OSC is the operation and support cost
RADC is the retirement and disposal cost

The research and development cost is estimated from the relationship:

$$RDC = \Sigma^{7}_{i=1} RDC_i$$

where RDC_i is the ith cost component of the research and development cost:

i = 1 (product planning)
i = 2 (engineering design)
i = 3 (system test and evaluation)
i = 4 (system/product life cycle management)
i = 5 (system/product software)
i = 6 (product research)
i = 7 (design documentation)

The production and construction cost is defined as:

$$PCC = \Sigma^{5}_{i=1} PCC_i$$

where PCC_i is the ith cost component of the production and construction cost:

i = 1 (manufacturing)

i = 2 (quality control)

i = 3 (construction)

i = 4 (industrial engineering and operations analysis)

i = 5 (initial logistics support)

The operation and support cost is defined as

$$OSC = \Sigma^{3}_{i=1} OSC_i$$

where OSC_i is the ith cost component of the operation and support cost:

i = 1 (system/product distribution)

i = 2 (sustaining logistic support)

i = 3 (system/product operations)

The retirement and disposal cost is given by:

$$RADC = SURC + [a(UMA)(IDC - RV)]$$

where,

SURC is the system/product ultimate retirement cost

RV is the reclamation value

IDC is the cost of item disposal

a is the factor for depreciation of item performance due to age

UMA is the number of unscheduled maintenance actions

Model VI

This model is concerned with the life cycle cost of a car including its disposal cost. The model is represented mathematically as:

$$LCC = AC_c + \Sigma^{NL}_{i=1} (SMC_i + OC_i + URC_i) + DC$$

where,

LCC is the life cycle cost of the car

AC_c is the acquisition cost

NL is the lifetime of the car in years

SMC_i is the scheduled maintenance cost of the car for each year i

OC_i is the operating cost of the car for each year i

URC_i is the unscheduled repair cost of the car for each year i

DC is the disposal cost

Model XII

Model XII deals with the life costing of appliances.

The appliance life cycle cost is expressed as:

$$LCCA = ACA + \Sigma^{LY}_{i=1} CEN_j [FC(1+R_f)^j / (1+i)^j]$$

where,

LCCA is the life cycle cost of the appliance

ACA is the acquisition cost

LY is the useful life of the appliance expressed in years j is the discount rate (%)

CEN_i is the ith year's energy consumption expressed in standard units

R_f is the fuel price increase per standard unit (%)

FC is the cost of a standard unit of energy

APPENDIX C

The Time Value of Money

The widespread adoption of DCF (Discounted Cash Flows) to represent the time value of money within industry was demonstrated in a survey by Scapens et al. in 1982, which provided a study of UK and US practice of discounted cash flow techniques. They found that 84% of US companies and 54% of companies used DCF [Scapens et al. 1982].

Net Present Value (NPV)

This technique is the adoption of the above equations of PV, with the consideration of cash flows instead of a single sum of money. The NPV of a product is,

$$NPV = C^i_0 + C^i_1 / (1+r) + C^i_2 / (1+r)^2 + \ldots\ldots. + C^i_t / (1+r)^t + \ldots\ldots. + C^i_T / (1+r)^T$$

$$NPV = \Sigma^T_{t=0}\, C^i_t / (1+r)^t$$

where: C^i_t is the estimated cash flow for product i in year t

r is the discount rate

T is the life cycle of the product.

NPV provides a decision maker with today's price of the total investment required for a product life cycle.

Selecting the discount rate

The selection of the discount rate depends whether the company is financing the project through borrowed money or from capital assets. In the first case the discount rate must be equivalent to the actual cost of borrowing the money. However, if the product is to be financed through capital assets, such as retained income or funds from the issue of shares, then the discount rate must be derived from the current and future rate of return from the industry sector. The discount rate can have a critical effect on a product, with too high a rate favouring short term cash flows, while too low a discount rate will make long term future cash flows more attractive. Therefore the higher the discount rate used, the lower the impact of future cash outflows. However, this also has the effect of making future cash inflows, less significant.

In the UK and US, the most commonly used method of selecting the discount rate is through management judgement. Surveys quoted in Lumby [Lumby 1993] and undertaken in 1976 [Caresberg and Hope 1976] and in 1975 [Petty et al. 1975], found that between 40% and 55% of companies used a management determined discount rate that was not directly related to market forces. Between 10% and 20% of companies used the bank overdraft rate and the rate of interest on other funds.

Dealing with Inflation

An interest rate comprises of two components, the time value of money and the effects of inflation. Because inflation has become a significant factor to be considered when predicting future costs, it should be taken into account within the discount rate. This only applies in cases where all components of the cash flow have the same inflationary rates. Where for example labour and materials have differing inflationary rates, then a different approach should be taken. In cases where inflationary effects are the same for all components, then the following equation should be used,

$$d^1 = [(1+d) / (1+i)] - 1$$

or

$$(1 + d^1).(1 + i) = 1+ d$$

where: d^1 = net of inflation discount rate (real discount rate)

d = interest rate including inflation (nominal or market discount rate)

i = general rate of inflation

If different cost elements are expected to inflate at different rates, for instance if labour costs inflate more than material costs, then the calculation of NPV has to take a new approach. For example, assume that annual costs consist of two streams, C^1 and C^2, the first being labour costs with an expected inflation rate of *l*% and the second material costs with an inflation rate of *m*%. The initial capital costs are C_0 with the market rate of interest being *d*%. The resulting NPV equation would therefore be:

$$
\begin{aligned}
NPV = C_0 + \; & \\
& C^1 (1+l) / (1+d) + \\
& C^1 (1+l)^2 / (1+d)^2 + \ldots\ldots + \\
& C^1 (1+l)^t / (1+d)^t + \ldots\ldots + \\
& C^1 (1+l)^N / (1+d)^N \\
& \qquad + \\
& C^2 (1+m) / (1+d) + \\
& C^2 (1+m)^2 / (1+d)^2 + \ldots\ldots + \\
& C^2 (1+m)^t / (1+d)^t + \ldots\ldots + \\
& C^2 (1+m)^N / (1+d)^N
\end{aligned}
$$

Hence:

$$NPV = C_0 + \Sigma^N_{t=0} [(C^1 (1+l)^t + C^2 (1+m)^t) / (1+d)^t]$$

In a survey of large companies conducted in 1976 it was found that the most popular, but incorrect approach was to adjust the discount rate to take out effects of general inflation which is valid, but then to apply this to cash flows expressed in current prices. Only 15% of the survey took correct account of inflation in their investment appraisal calculations [Carsberg and Hope 1976].

In a later survey in 1978 [Westwick and Shohet 1978], 77% of companies were found to take inflation into account, with the most popular, but again incorrect method of raising cash flows in line with expected, specific rates of inflation and then also raising the discount rate.

A further survey in 1982 [Pike 1982], discovered that 89% of companies considered inflation in investment appraisal, where only 70% did in 1975. However, the most popular method was to adjust project cash flows to take into account general inflation. It was also found that a number of larger companies adjusted cash flows by specific inflation rates, or used current prices and applied a real rate of discount.

APPENDIX D

ANOVA

The following section provides a description of ANOVA.

Notation:

C.F. = Correction factor

e = Error

F = Variance ratio

f = Degrees of freedom

f_e = Degrees of freedom error

f_T = Total degrees of freedom

n = Number of trials

r = Number of repetitions

P = Percent contribution

T = Total (of results)

S = Sum of squares

S' = Pure sum of squares

V = Mean squares (variance)

Total Number of Trials:

To determine the effect of factor A on response Y, factor A is tested at L levels. Assuming n_1 repetitions of each trial that includes A_1. Similarly at level A_2 the trial is to be repeated n_2 times. The total number of trials is the sum of the number of trials at each level:

$$n = n_1 + n_1 + ... + n_L$$

Degrees of Freedom (DOF):

This is the measure of the amount of information that can be uniquely determined from a given set of data. For instance, a factor with 4 levels has a DOF 3 Additionally for an experiment with n trial and r repetitions has n * r trial runs the total DOF is:

$$f_T = n * r - 1$$

Sum of Squares:

This is the measure of deviation of the data from the mean value of the data. Therefore:

$$S_T = \Sigma^n_{i=1} (Y_i - Y_{ave})^2$$

where Y_{ave} is the average value of Y_i

Similarly the sum of squares of deviations S_T , from a target value Y_o is given by:

$$S_T = \Sigma^n_{i=1} (Y_i - Y_{ave})^2 + n(Y_{ave} - Y_o)^2$$

Variance measures the distribution of the data about the mean of the data. This data is only representative of all possible data and therefore, DOF rather than the number of observations is used in the calculation:

Variance = Sum of Squares / DOF

$$V = S_T/f$$

When the average sum of squares is calculated about the mean, it is known as the general variance. The general variance σ^2 is defined as:

$$\sigma^2 = 1/n\Sigma^n_{i=1} (Y_i - Y_{ave})^2$$

If:

$$m = (Y_{ave} - Y_o)$$

then:

$$S_T = n\,\sigma^2 + nm^2 = n(\sigma^2 + m^2)$$

Thus, the total sum of squares of deviations S_T from the target value Y_0 is the sum of the variance about the mean and the sum square of the deviation of mean from the target value multiplied by the total number of observations made. The total sum of squares S_T provides an estimate of the sum of the variations of the individual observations about the mean Y_{ave} of the experimental data and the variation of the mean about the target value Y_0. When the total sum of squares S_T, is separated into its constituents, the variation can be understood and an appropriate strategy developed to increase the robustness of the subject of the study.

Mean Sum (of Deviations) Squared

If:

$$T = \Sigma^n_{i=1} (Y_i - Y_0)$$

which represents the sum of all deviations from the target value, then the mean sum of squares of the deviation is:

$$S = T^2/n = [\Sigma^n_{i=1} (Y_i - Y_0)]^2 / n$$

then:

$$S_m = 1/n[(Y_1 - Y_0) + ...+ (Y_n - Y_0)]^2$$

$$S_m = 1/n[(nY_{ave} - nY_0)]^2$$

$$S_m = n^2/n[(Y_{ave} - Y_0)]^2$$

$$S_m = nm^2$$

The statistical estimate of this equation includes one part of general variance. Therefore the statistically expected value by $E(S_m)$ is:

$$E(S_m) = S_m = \sigma^2 + nm^2$$

The term (S_T - S_m) is referred to as the error sum of squares and equates to:

$$S_e = S_T - S_m = (n - 1)\sigma^2$$

APPENDIX E

Orthogonal Arrays

Orthogonal arrays increase the efficiency of experimental analysis. By using an L8 orthogonal array, 8 experiments are required. The factor level combinations during the 8 experiments are defined by the array. The array is amenable to statistical analysis with a high degree of confidence. The next lower array is the L_4 , which requires 4 experiments and can handle up to 3 factors at 2 levels. When a situation is between 4 and 7 factors at 2 levels, an L_8 array is used. Since all factors have the same number of levels, the factors can be assigned to any one column. For situations where a higher number of factors, levels and interactions are involved a number of other orthogonal arrays are available [Roy 1990].

Where factors have different levels, then modification of the standard array is required. Therefore individual columns can be upgraded, from 2 levels to 4 or 8 levels; or downgraded from 4 levels to 3. This method of reducing levels is termed Dummy Treatment. A Degree Of Freedom (DOF), for a column is its number of levels less one. Therefore a DOF for a 4 level column is 3. So in order to create a 4 level column, three 2 level columns are required to provide the same DOF. Therefore to change one column of an L_8 to a 4 level column, 3 columns are combined. If a column of an L_{16} is to contain an 8 level column, seven of the 15, 2 level columns are combined.

L_8 Example:

L_8 Array

Columns	1	2	3	4	5	6	7
Exp't No.							
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

The aim of this example is to design an array with one factor at 4 levels and three other factors at 2 levels.

A = 4
B, C, D, E = 2

The total DOF is 7, with A having 3 and the rest, 1. An L_8 which has 7 DOF appears suitable. The first stage is to select a set of three interacting columns of the L_8 linear graph. Two of the three, in this case 1 and 2 are selected and the columns of the two selected are combined using the following rule:

1st Column	2nd Column		Combine to:
1	1	=	1
1	2	=	2
2	1	=	3
2	2	=	4

Columns one, two and three are replaced by this new combined column. The result is as follows:

Columns	New Column	4	5	6	7
Exp't No.	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	2	1	1	2	2
4	2	2	2	1	1
5	3	1	2	1	2
6	3	2	1	2	1
7	4	1	2	2	1
8	4	2	1	1	2

An 8 level column can be established by combining a set of seven 2 level columns of an L_{16} array. The linear graph identifies which are the interconnecting columns and the following rule applied to create a new combined column:

1st Column	2nd Column	3rd Column		Combine to:
1	1	1	=	1
1	1	2	=	2
1	2	1	=	3
1	2	2	=	4
2	1	1	=	5
2	1	2	=	6
2	2	1	=	7
2	2	2	=	8

In the same way that 2 level columns can be combined into higher levels, then so higher levels columns can be decomposed into lower level columns. If an experiment has four factors, A, B, C and D, of which A has 2 levels and the rest 3, then the DOF is 7. The nearest array is the L_9 , with four 3 level columns with a DOF of 8. This array can be used if one column can be reduced to 2 levels.

APPENDIX F

Costing Systems

The following appendix provides a review of costing systems, which as described throughout the thesis will undoubtedly have an impact upon how companies view EOL product take back.

Financial accounting requires that costs are matched against revenues to calculate profit. Hence, any unsold finished stock or partly completed stock (work in progress) is not included in the cost of goods sold which is matched against revenue in a given period. In an organisation which produces a wide range of different products it is necessary, for stock valuation purposes, to charge costs to an individual product. The total value of the stocks of completed products and work in progress plus any unused raw materials forms the basis for determining the stock valuation which is deducted from the current periods costs when calculating profit. Costs are therefore allocated to each individual product to provide the necessary information for financial accounting reports. Cost accounting was developed to provide this information.

Period and product costs

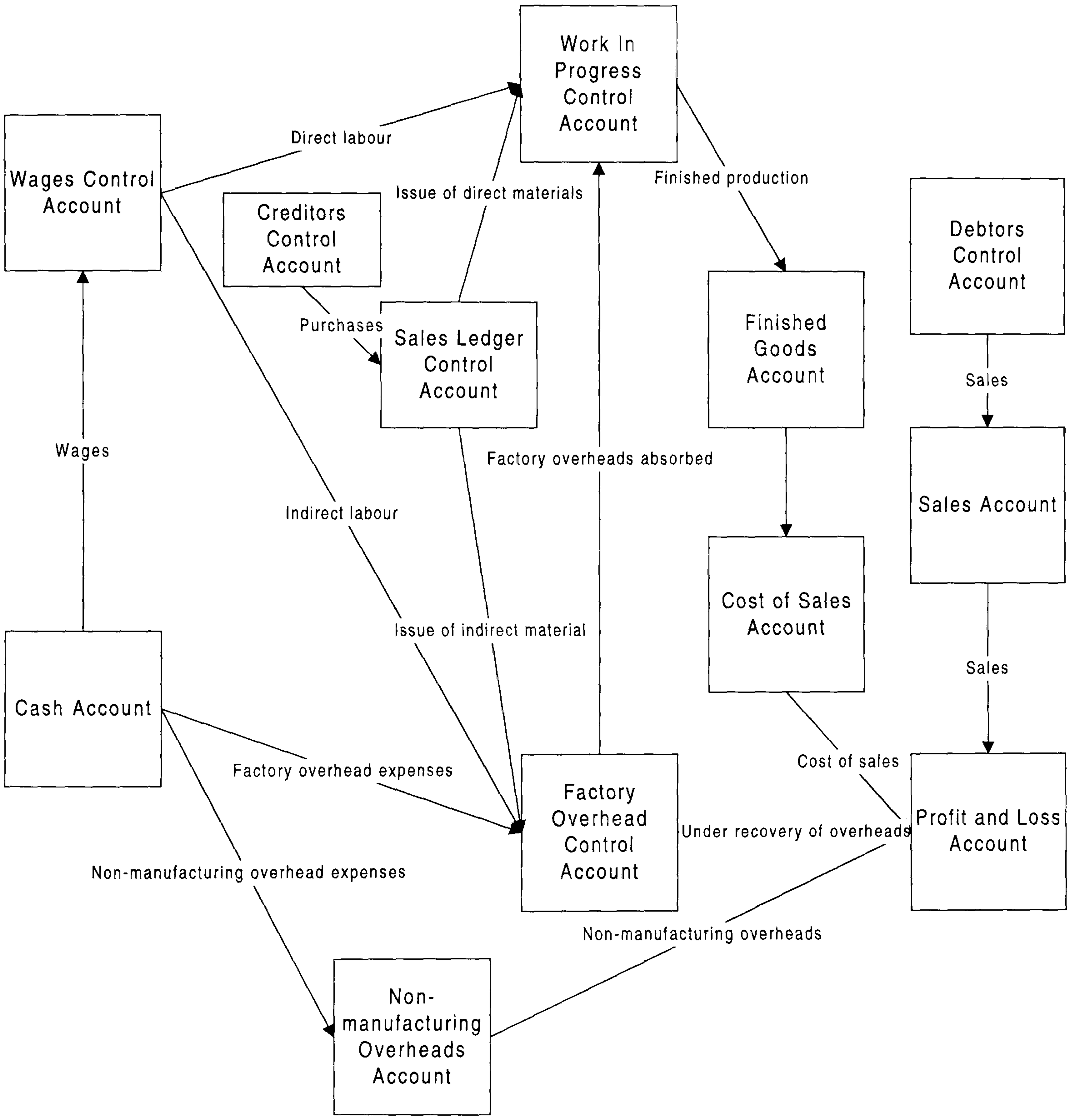
For stock valuation and profit measurement it is important to distinguish between assets and expenses. Assets are recorded on the balance sheet as the resources that have been acquired and which are expected to contribute to future revenue. When the resources are sold they are considered to be expenses in the profit and loss account. For example, the costs incurred in producing goods for sale where such goods remain unsold and held in stocks are recorded as assets in the balance sheet. When the goods are sold, these assets become expenses as represented in the cost of goods sold calculation and are matched against sales revenue to calculate profit. Therefore an expense is a cost which has been consumed in earning revenue.

In the UK, a Statement of Standard Accounting on stocks and work in progress was published by Accounting Standards Committee in 1975 (SSAP 9) and revised in 1988. These standards require that for stock valuation, only manufacturing costs should be included in the calculation of product costs. Therefore accountants classify costs as product costs and period costs. Product costs are those costs which are identified with goods produced for sale. Period costs are those costs which are not included in the stock valuation and as a result are treated as expenses in the period in which they were incurred. In a manufacturing organisation all manufacturing costs are regarded as product costs and non-manufacturing costs are regarded as period costs. Hence, administration, sales and logistics are considered as period costs. Traditionally, accountants have not included non-manufacturing costs as part of the product cost, although the relatively new technique of Activity Based Costing advocates the adoption of such principles.

Direct materials, direct labour and manufacturing overhead

In manufacturing organisations the calculation of product costs consists of three elements, direct materials, direct labour and manufacturing overhead. Direct materials consist of all those materials which can be physically identified with a specific product. For example, steel to produce a car panel is a direct material, whereas materials used for the repair of the machine pressing a number of different car panels would be classified as indirect materials. Indirect materials form part of the manufacturing overhead cost. Direct labour consists of those labour costs which can be traced to a particular product such as an assembly labour cost. However, the labour cost of a stores department are classified as indirect labour costs and again form part of the manufacturing overhead cost. The prime cost is the composition of the direct costs, the direct materials and direct labour. Manufacturing overhead consists of all manufacturing costs, other than direct costs. In order to calculate the total manufacturing cost for stock valuation, the direct cost per unit is multiplied by the number of units. In contrast overheads are for the period are summed and shared among the products that have been manufactured during the period based upon a method of apportionment.

It is preferable to apportion or charge overheads to products using departmental overhead rates rather than using a blanket overhead rate. The most frequently used overhead rate is the direct labour hour method for non machine departments and the machine hour rate for machine departments. Other methods of recovering overheads, such as the direct wages percentage, units of output and direct materials tend to be less favoured. Non-manufacturing costs have traditionally been classified as period costs and were not charged to products. However, techniques such as Activity Based Costing now advocate that such costs should be allocated to products.



A typical manufacturing costing system

Variable, semi-variable and semi-fixed costs

The above relates to historic costs and revenues for stock valuation. However, costing also includes planning the costs and revenues concerned with the future. The terms variable, semi-variable and semi-fixed are used to describe how cost reacts to changes in activity. Variable costs relate directly to the proportion of activity and are therefore linear. Examples of such costs include direct materials and power. Fixed costs remain constant over a period of time. Examples include depreciation of company buildings and the leasing costs of cars for the sales force. Unit fixed costs decrease proportionally with the number of products produced. Fixed costs are often increased to reflect inflationary rises. Semi-variable costs include both a fixed and a variable component. Hence, maintenance is a semi-variable cost, consisting of planned maintenance which occurs whatever the level of activity and a variable element which is directly related to the level of activity. Semi-fixed costs are fixed for a given level of activity, but increase by a constant amount at some point in time.

Relevant and irrelevant costs and revenues

Costs and revenues can be classified dependant upon whether they are relevant to a decision. For example, faced with the choice of using a Rolls Royce or Mini to make a journey, the car tax will be irrelevant as it will remain the same whichever mode of transport is selected.

In the short term not all costs and revenues are relevant for decision making. Therefore it is important that the classification of costs is undertaken correctly with the conflicting requirements of cost classification for stock valuation and decision making.

Sunk costs

Such costs originate from historic decisions which are now irreversible. Hence, stock which is obsolete is classified as a sunk cost.

Opportunity costs

An opportunity cost is a cost which measures the opportunity which is lost when a course of action eliminates an option that could be provided by another course of action.

Incremental (marginal) costs / revenues

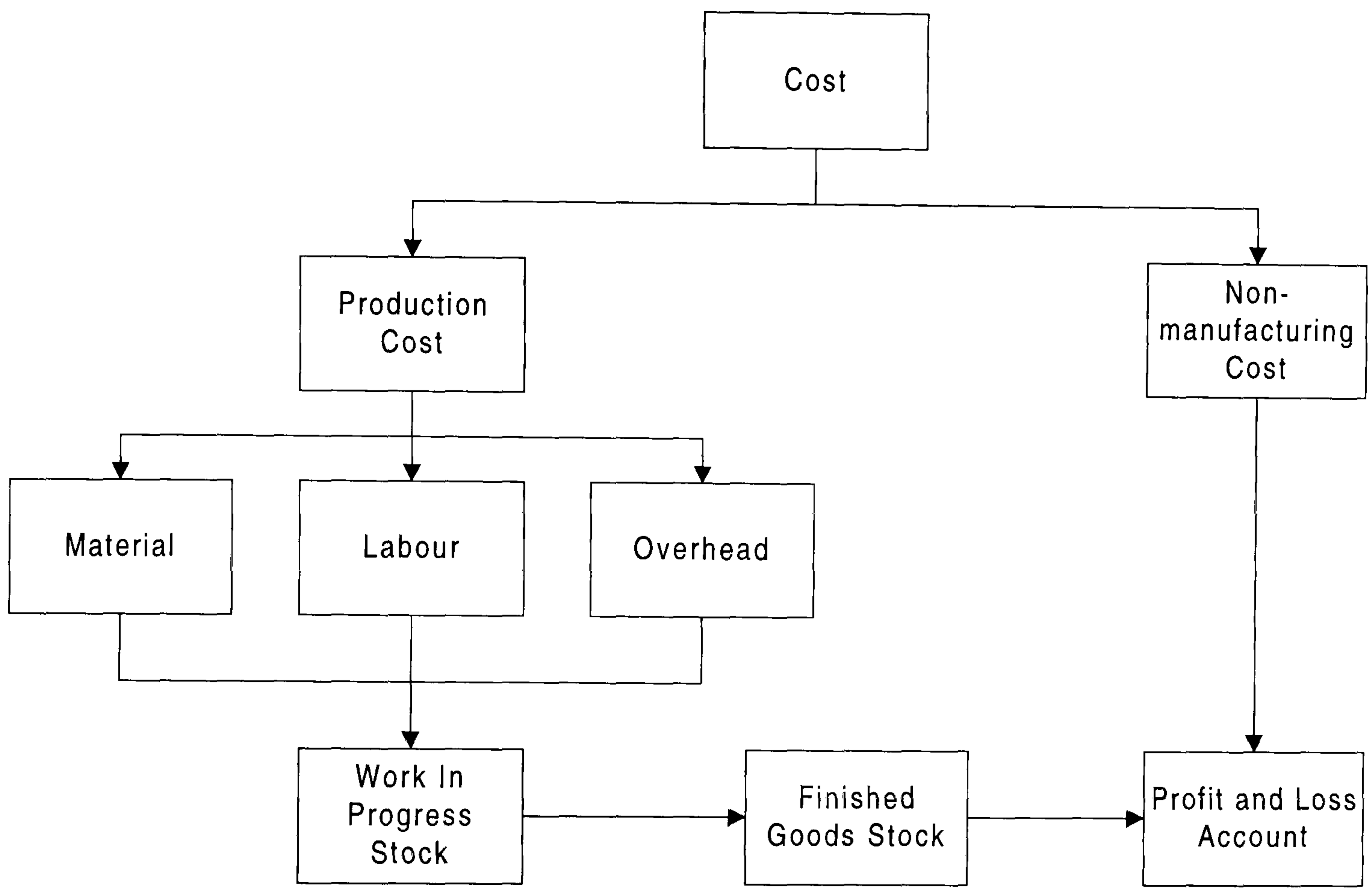
Incremental costs and revenues are the additional costs or revenues which arise from the production or sale of a group of additional units. Hence, if fixed costs change as a result of a decision, the increase in costs represents an incremental cost. The increase in the salaries of assembly workers is therefore an incremental cost, whereas the fixed cost of leasing the premises will not change whatever the level of production and hence the incremental cost is zero.

Just In Time (JIT) purchasing

Organisations are increasingly attempting to reduce stock levels to a minimum through creating closer relationships with their suppliers and arranging more frequent deliveries of smaller quantities. The objective of JIT purchasing is to purchase goods at the point of use in production. Suppliers are expected to guarantee the quality of material. Obviously, such a strategy results in enormous savings in materials handling and in stock. However, if recycled components are held in reserve for use in production or spares, the cost savings in terms of not having to purchasing new components will be to some extent reduced by the cost of storage.

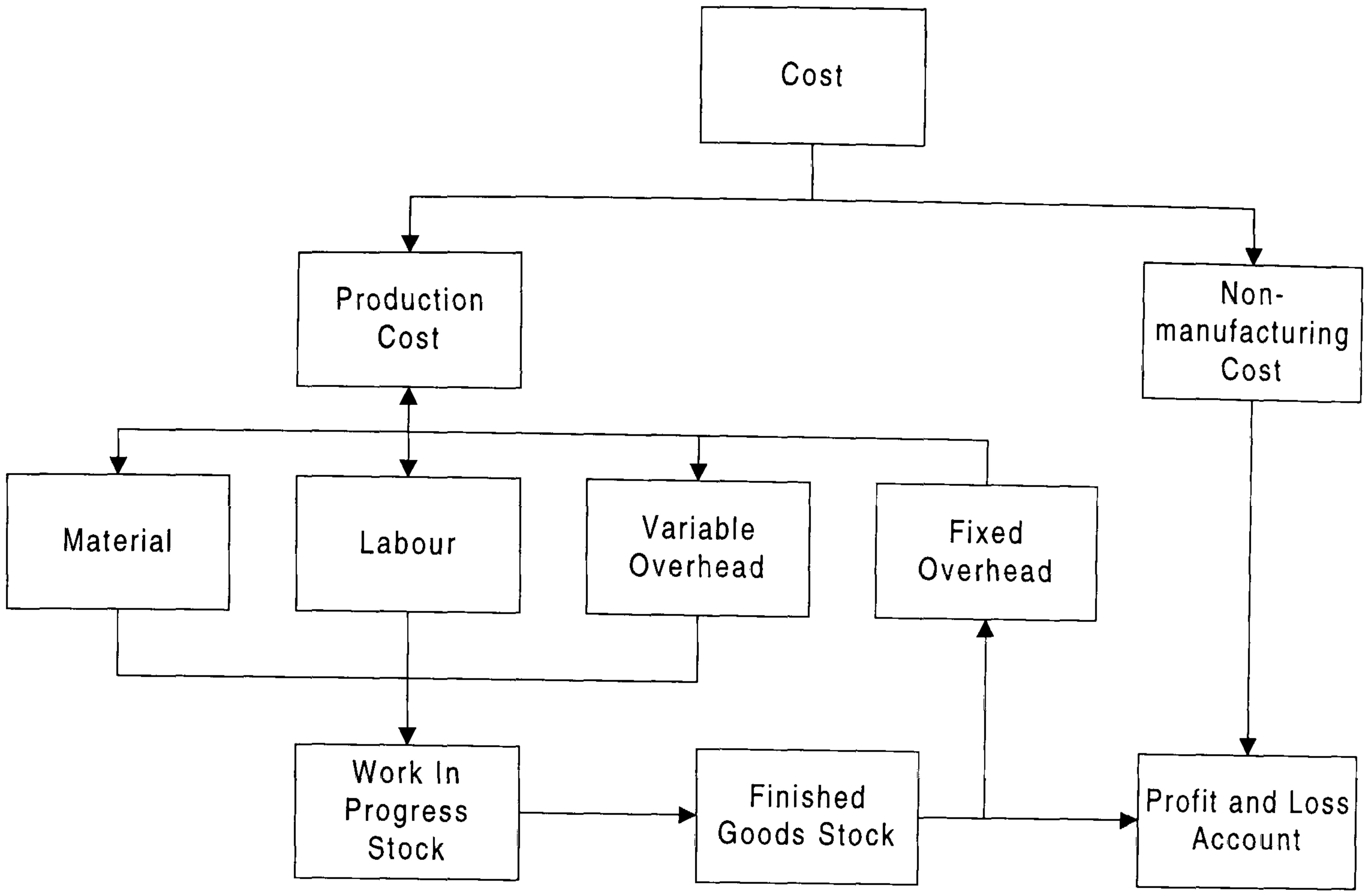
Absorption and variable costing

Traditionally, allocation of manufacturing costs to products and unsold stocks was apportioned based upon their total cost of manufacture. Non-manufacturing costs were treated as period costs and deducted from total profit and excluded from stock valuation. A costing system based on these principles is known as absorption or full costing. An alternative is variable costing, marginal costing or direct costing. Under this alternative costing system, only variable manufacturing costs are allocated to products and included in the stock valuation. Fixed manufacturing costs are not allocated to the product, but are treated as period costs and deducted from total profit. Both systems treat non-manufacturing costs as period costs. Hence, the main difference between the two systems is whether manufacturing fixed overhead should be regarded as a product or period cost.



Absorption Costing

It is argued that variable costing provides more useful information for decision making, however it is also claimed that similar cost information can be provided by absorption costing. The main advantage of variable costing is that profit is reflected as a function of sales, whereas in absorption costing, profit is a function of sales and production. For example, with absorption costing, when all factors remain unchanged, sales can increase but profit may decline. With variable costing, profits increase with sales.



Variable Costing

Costing for EOL

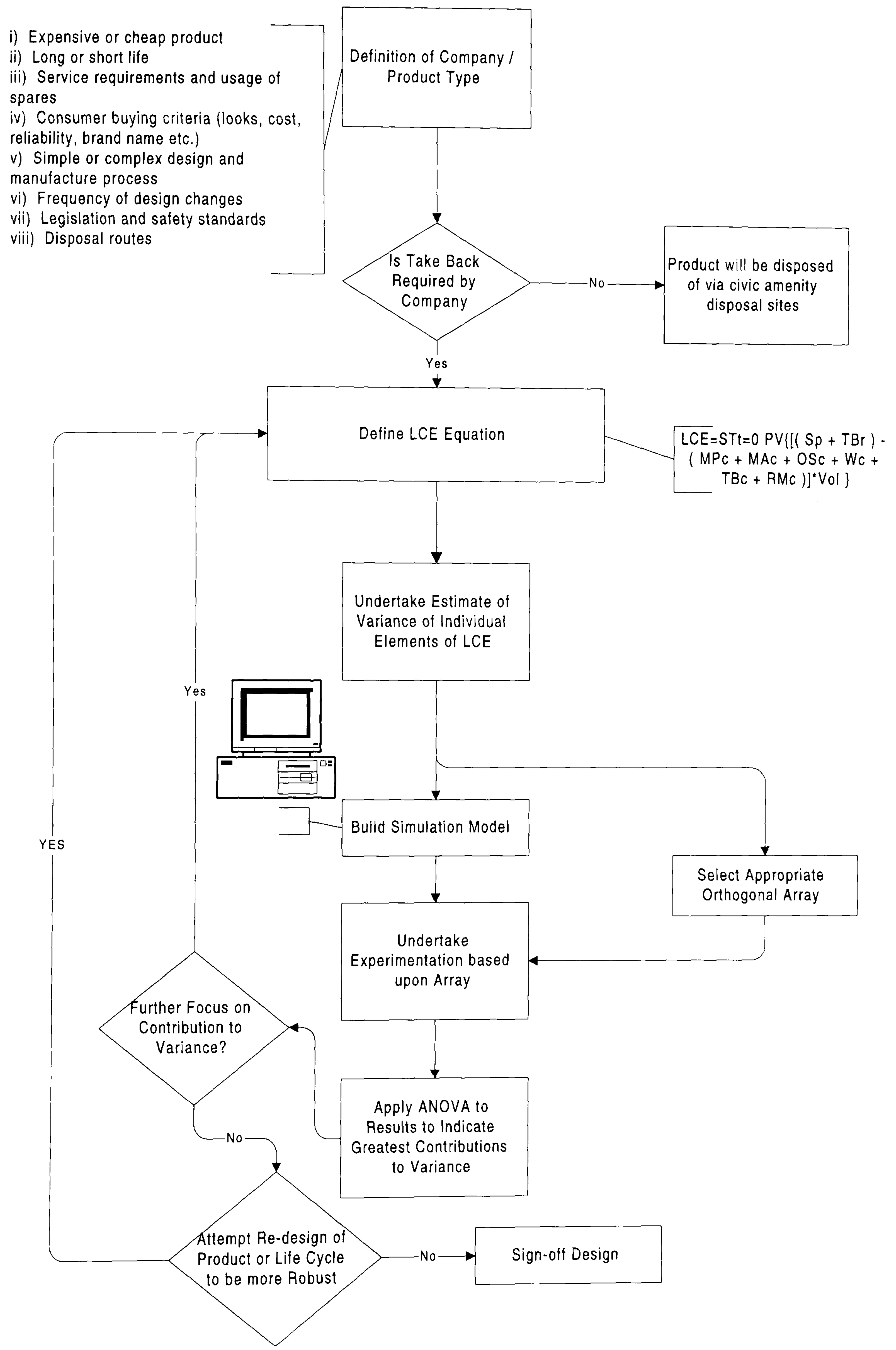
The Statement of Standard Accounting Practice on Stocks and Work in Progress (SSAP 9) does not provide guidance on the accounting of product take back at EOL, however, they give advice on long term contracts, which are similar to take back where a future action will involve cost to realise a profit. The SSAP 9 provides the following guidance on the attributable profit to be taken up for a particular period:

Where the business carries out long-term contracts and it is considered that their outcome can be assessed with reasonable certainty before their conclusion, the attributable profit should be calculated on a prudent basis and included in the accounts for the period under review. The profit taken up needs to reflect the proportion of work carried out at the accounting date and to take into account any known inequalities of profitability at the various stages of a contract. The procedure to recognise profit is to include an appropriate proportion of total contract cost as turnover in the profit and loss account as the contract activity progresses. The costs incurred in reaching that stage of completion are matched with this turnover, resulting in the reporting of results that can be attributed to the proportion of work completed.

Where the outcome of long-term contracts cannot be assessed with reasonable certainty before the conclusion of the contract, no profit should be reflected in the profit and loss account in respect of those contracts although, in such circumstances, if no loss is expected it may be appropriate to show as turnover a proportion of the total contract value using a zero estimate of profit.

If it is expected that there will be a loss on a contract as a whole, all of the loss should be recognised as soon as it is foreseen (in accordance with the prudence concept).

AMDEL


i) Expensive or cheap product
ii) Long or short life
iii) Service requirements and usage of spares
iv) Consumer buying criteria (looks, cost, reliability, brand name etc.)
v) Simple or complex design and manufacture process
vi) Frequency of design changes
vii) Legislation and safety standards
viii) Disposal routes
Definition of Company / Product Type
Is Take Back Required by Company
No
Product will be disposed of via civic amenity disposal sites
Yes
Define LCE Equation
LCE=STt=0 PV{[(Sp + TBr) - (MPc + MAc + OSc + Wc + TBc + RMc)]*Vol }
Undertake Estimate of Variance of Individual Elements of LCE
Yes
Build Simulation Model
Select Appropriate Orthogonal Array
YES
Undertake Experimentation based upon Array
Further Focus on Contribution to Variance?
Apply ANOVA to Results to Indicate Greatest Contributions to Variance
No
Attempt Re-design of Product or Life Cycle to be more Robust
No
Sign-off Design

All companies and products are different, therefore it is useful in this definition stage to identify the positioning of the proposed product within the market place. Some products will clearly be unsuited to EOL product take back. For example, does the market place require frequent design modifications, which will effect the ability to use spare components from EOL products in service applications? Such a classification may be based upon the following:

i) Expensive or cheap product
ii) Long or short life
iii) Service requirements and usage of spares
iv) Consumer buying criteria (looks, cost, reliability, brand name etc.)
v) Simple or complex design and manufacture process
vi) Frequency of design changes
vii) Legislation and safety standards
viii) Disposal routes

If a company concludes that EOL product take back is unlikely to occur then it should focus effort on increasing the efficiency of manufacture, assembly and possibly service. Section 7.2 describes the use of methodologies, such as DFM/A, that can be used for this purpose.

In order to assist the definition stage AMDEL provides a generic life cycle model, which builds upon Life Cycle Costing. The provision of such a model provides a structure and direction about which the design team can work. The model divides the definition into sections of the life cycle, allowing the various members of the design team to focus on their relevant area. Although in no way is this model meant to be prescriptive, it will typically accelerate the definition process of AMDEL. Hence, AMDEL provides a model termed the Life Cycle Economic Model:

$$LCE=\Sigma^{T}_{t=0} PV\{[(Sp + TBr) - (MPc + MAc + OSc + Wc + TBc + RMc)]*Vol \}$$

where:

T is the time period in years to EOL

PV is the present value

Sp is the price charged for the product

TBr is the revenue generated from taking back the product, in terms of material or components

MPc is the raw material procurement cost

MAc is the manufacture and assembly cost

OSc is both the internal and external operational and support cost of the product

Wc is the warranty cost to the producer

TBc is the cost of product take back, including logistics and incentives

RMc is the remanufacture cost

Vol is the volume of sales in each year

Although the equation is generally aimed at a product, there is no restriction upon it being applied to individual components. However, the philosophy of the methodology is that it should consider the whole product in order to direct the focus of the design team upon those individual components which are critical to the economic viability of the product life cycle.

Following definition of the LCE, the next step is to generate estimates of variance for the individual elements within the LCE and their relationships. For example, a low number of product sales may result in differing assembly and disassembly technologies and hence costs being incurred.

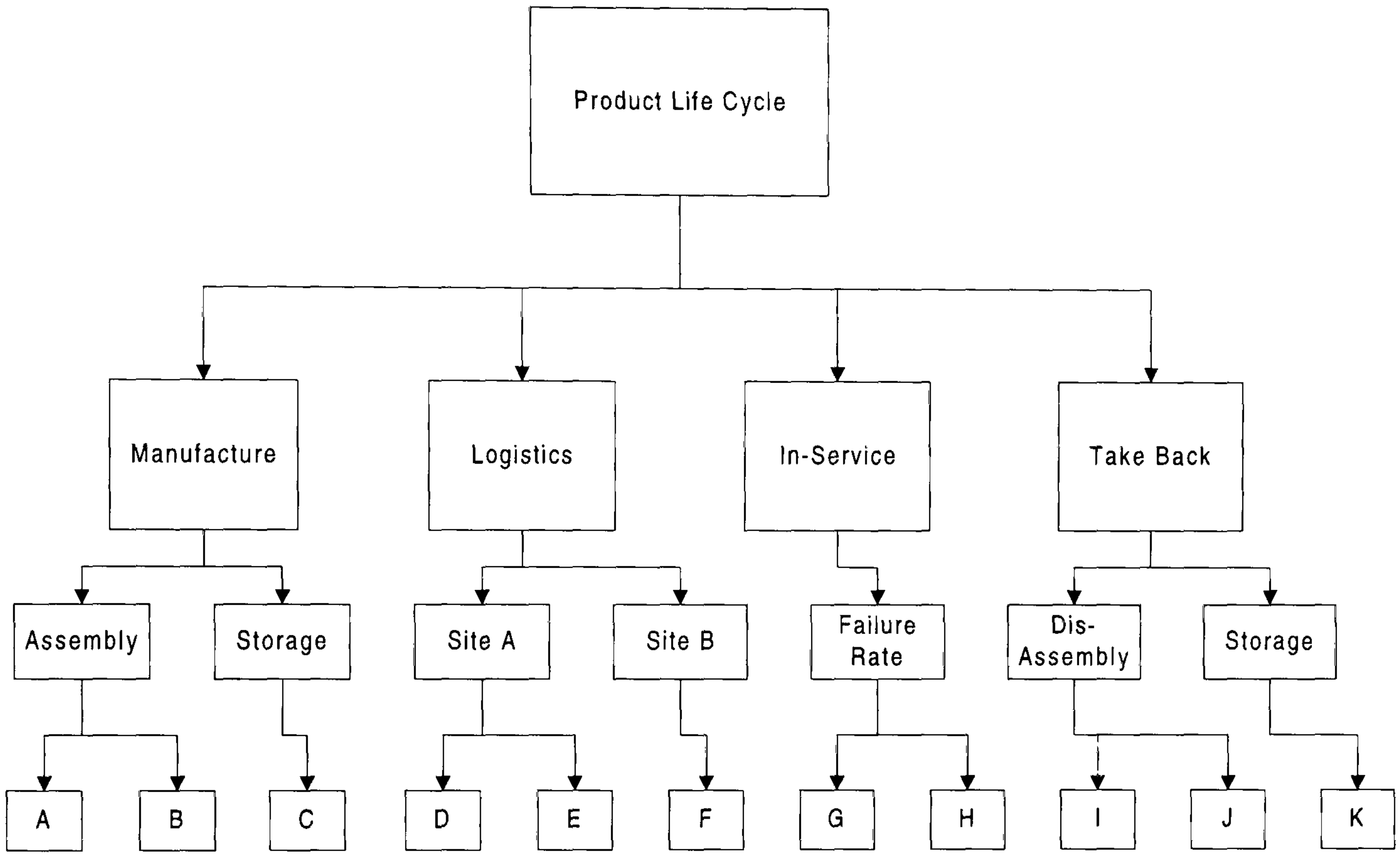
The definition phase provides a starting point which results in an equation that represents the economics of a product design. The final phase of AMDEL involves experimentation and analysis, but before this can be undertaken a model of the equation has to be established so that raw data can be applied to the model and outputs observed. In a simple LCE, an equation can be used to manually undertake experimentation. However, an LCE model typically comprises of a vast amount of data which has to be collated. The manual recording of such large amounts of data in the current age of computer tools is not acceptable. Hence, in order to allow the efficient use of AMDEL it is appropriate to adopt some form of computer aided assistance.

In chapter 6, an approach to experimentation using orthogonal arrays was introduced, as part of the process of ANOVA. Based upon the number of elements in the LCE an appropriate array to direct the experimentation has to be selected. Such an orthogonal array can be selected based upon the criteria set out in Appendix E.

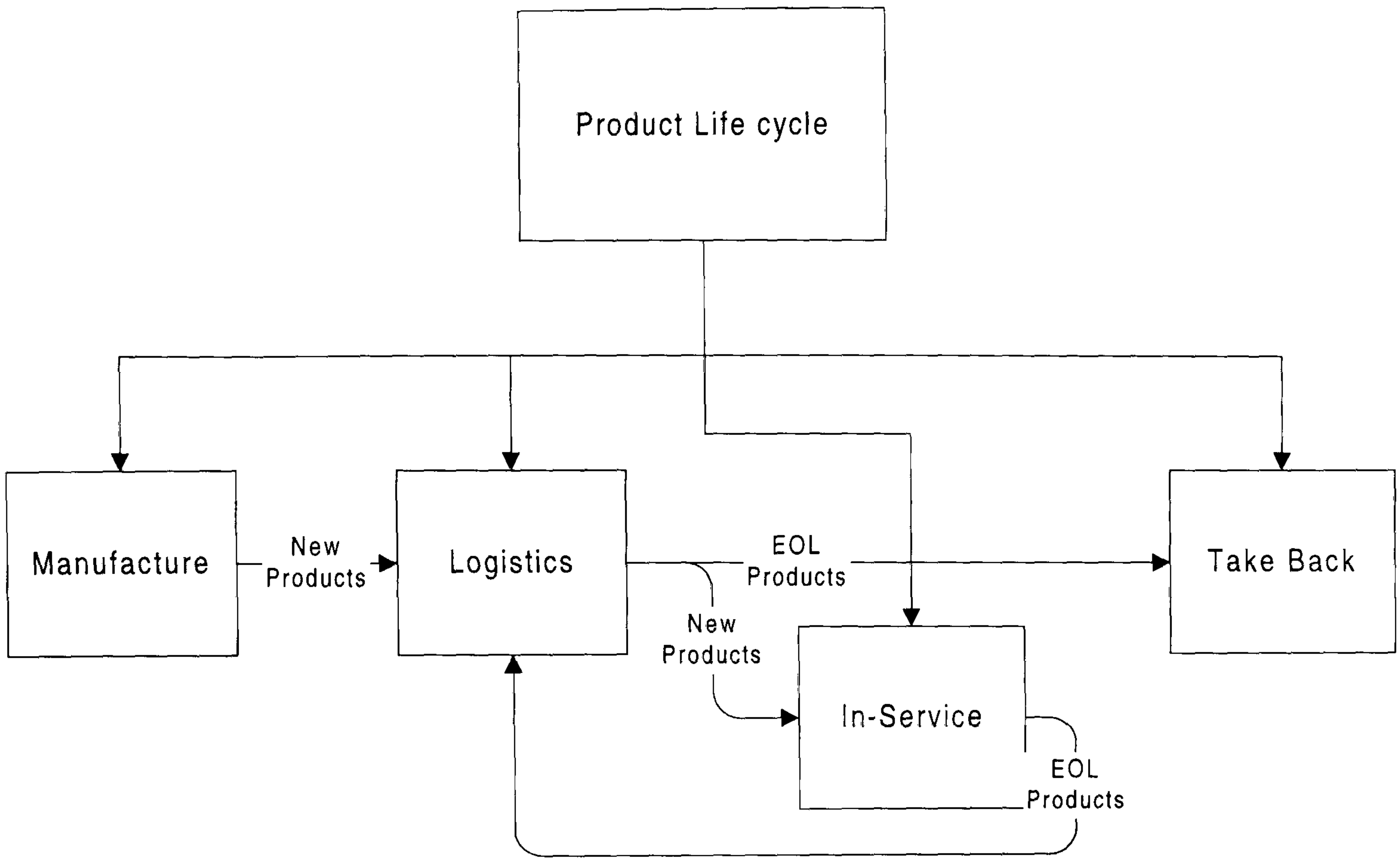
Once the model has been defined and a computer model generated, structured experimentation and analysis can be undertaken using an orthogonal array. The results will identify at the highest level those life cycle variables of a product's design which are the main drivers of economic life cycle variability. The design team will then decide if the analysis is required in greater depth in a specific area and which if so, will re-conduct the analysis, but to a greater level of detail, redefining the LCE, model and experimentation. If they feel that having conducted the analysis that a particular area of a design is the problem, then they will attempt to re-design the product. However, the value achieved in improving a design should exceed the cost expended. The use of a life cycle economic model, such as AMDEL, helps to identify the point at which a design should be finalised. For example, if the analysis identifies that profitability will vary between £1 and £3 million then it is probable that the company would not invest further in the design. However, if the analysis demonstrates that profitability will vary between a loss of £0.5 and a profit of £1 million, then it is likely further design effort would be expended.

AMDEL Hierarchy

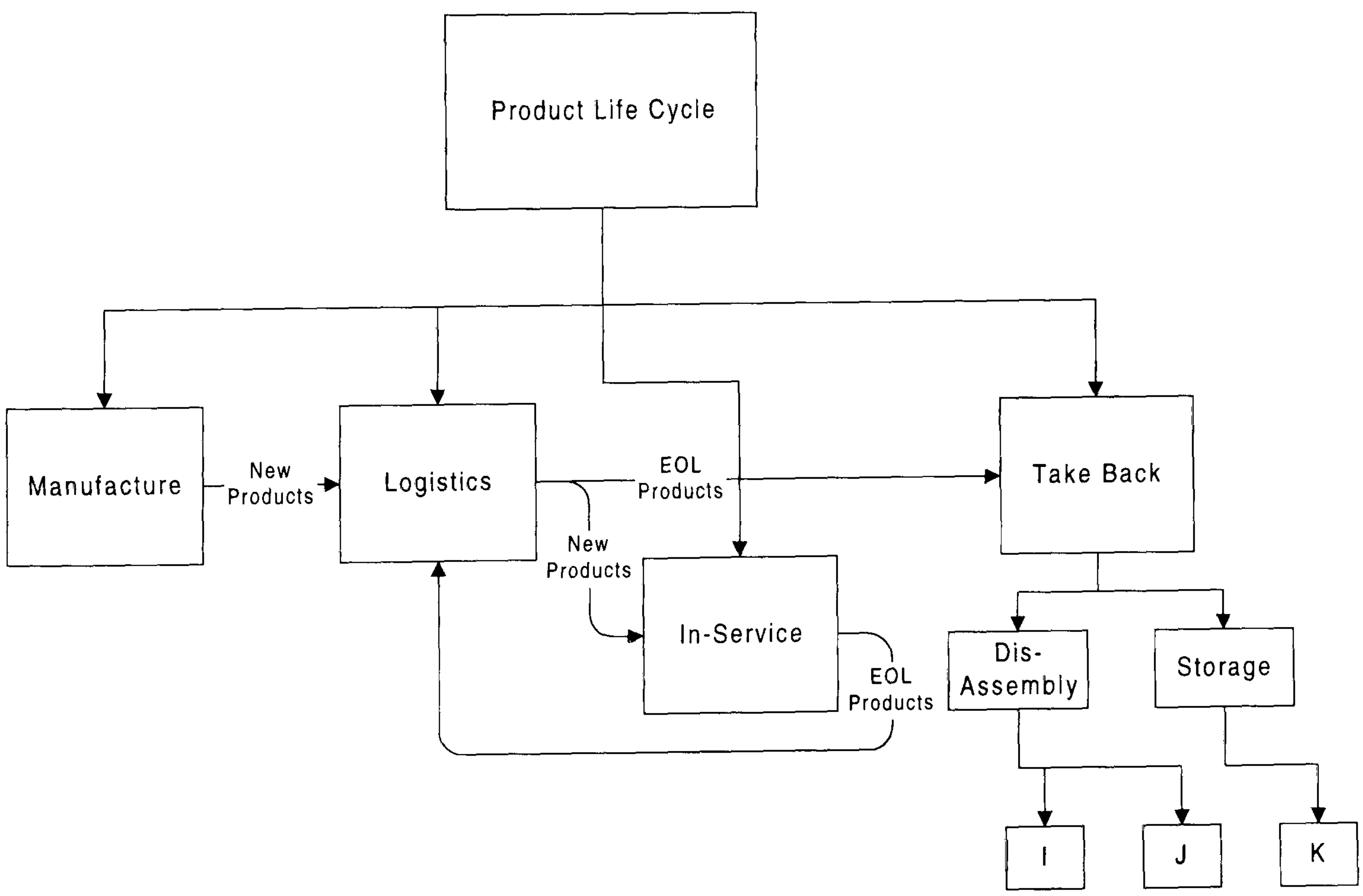
The chart below demonstrates the typical product life cycle hierarchy.



AMDEL does not advocate modelling the entirety of the product life cycle. Initially, analysis is performed on the highest level, demonstrated by the manufacture, logistics, in-service and take back boxes.



Then, based upon the ANOVA analysis, the model is developed into the lower component levels, demonstrated by boxes A to K. However, if the initial analysis identifies that the profitability of take back is critical to the overall profit variability, then the model would be developed as follows:



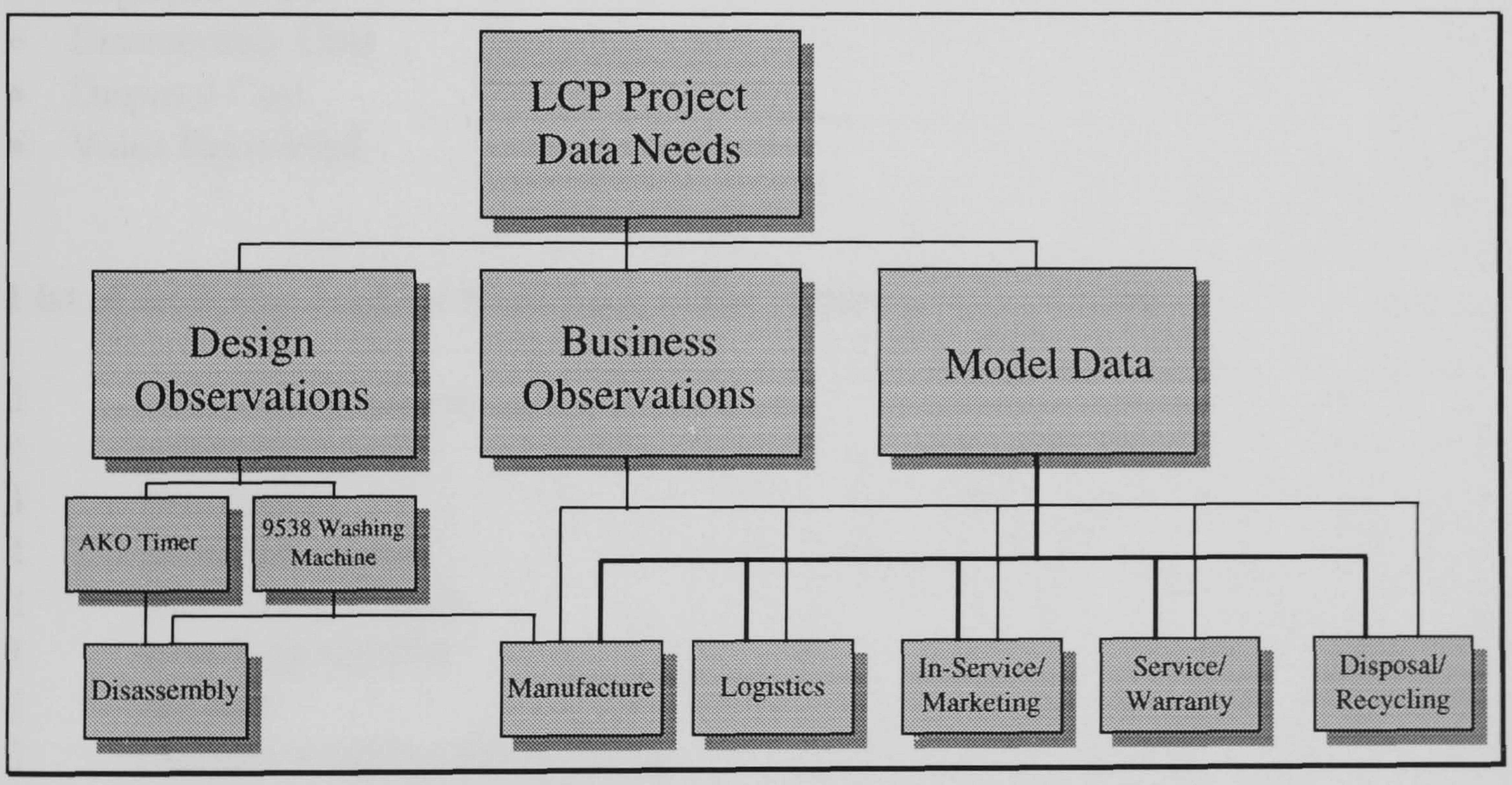
The diagram demonstrates that the model is only developed down to component level in the take back operation, where ANOVA has deemed it necessary.

APPENDIX H

The Case Study

The case study focused on a single product which at approximately 100,000 units per annum, accounts for approximately 30% of the company's front-loading washing machine market and 25% of their total domestic white goods market. The product retails at approximately £400 and some 20% of sales are via direct home delivery.

The full life-cycle of the machine was investigated; from raw materials through manufacture, use, service, disposal and recycling/refurbishing. Data was gathered from various company functions and a washing machine was disassembled at Cranfield University in order to gain an appreciation of the product and highlight any assumptions that would be required throughout the project, as well as establishing a disassembly precedence for the machine (complete with times; component masses; materials types; and order of disassembly).



Data Collection

The data was used to generate the life cycle model, the most time intensive part of the project, mainly due to validating the model within the various company departments that had supplied data. This was because various members disagreed with some of the initial data values and demonstrates the need to conduct the definition phase of AMDEL. For example, the service function argued that refurbished motors had a reliability level equal to new motors and could be used in new production, however manufacturing were concerned about consumer image and would not allow their use in new products.

Summary of the types of data collated:

Manufacturing Data
- Raw Material Cost
- Manufacturing Cost
- Assembly Cost

Purchase Data
- Selling Price
- Sales Forecast

Post Purchase Data
- Design Life
- Service/Warranty Costs
- Volume return rate per year
- Reclaim cost
- Logistics costs
- Disassembly Cost
- Disposal Cost
- Value Recovered

List of tools required for washing machine disassembly exercise:

1	electric screwdriver
1	power socket-set
1	wire cutters
1	pliers (fat-edged)
1	pliers (long-nosed)
1	three legged puller
1	hammer
1	(digital) weighing scales (<5kg)
1	weighing scales (5kg - 70kg)
1	stop-watch
1	video camera & cassette (with time-display function)
1	camera & film

Disassembly precedence:

Order	Item	Fastening technique	Time (secs)
1	Top cover	2 x hexhead	20
2	Transit bracket • sub-bracket • 2 x plastic spacer	3 x hexhead	20
3	Motor • pressure switch removal (from motor unit) • pulley belt (disassembly constraint) • 1 x cable tie	2 x 1/2" bolt	120 30
4	Motor mount bracket (inaccessibility due to drum)	2 x 10mm nut	45
5	Wiring harness removal (upper accessible parts)	13 direct connect/2 IDC/3 block	60
6	Dispenser inlet pipe	3 x hose clip	30
7	Solenoid valves	4 x hexhead	20
8	Mains filter	1 x 1/2" nut	10
9	Mains cable	1 x 6mm nut/1 x hexhead	65
10	Cable hook	1 x hexhead	5
11	Lower back panel • plastic hose clip	10 x hexhead	60
12	Back panel cover	4 x hexhead	15
13	Discharge hose	1 x hose clip	5
14	Dispenser drawer	(push fit)	2
15	Control knob	1 x hexhead	15
16	Console panel • foam tape	6 x hexhead	30
17	4 x Switch button	(push fit)	10
18	Switch bank	2 x hexhead	10
19	Timer unit • timer • module • pressure switch	1 x hex head + wires	80
20	Door unit • glass bowl • plastic trim • door lock	2 x nuthead screws	20
21	Seal resistant wire	1 x snap fit assly	7
22	Latch cover	2 x hexhead	10
23	Front panel	6 x hexhead	45
24	Hinge	2 x hexhead	15

25	Dispenser assly	4 x hexhead	20
26	Drum inlet hose	2 x cable tie	5
27	Console back plate Earth wire removal	6 x hexhead 1 x 7mm nut	30 10
28	Interlock assembly (includes latch cover)	2 x hexhead	20
29*	Drum unit assembly • BEAB safety strap • pump inlet hose (constraint) • pump electric wiring	2 x shock absorber 1 x 10mm bolt 1 x hose clip 1 x IDC	* 30 5
30	Pump inlet hose	1 x hose clip	10
31	Pump	2 x 8mm nuthead screw	35
32	2 x Suspension unit	2 x 13mm nut	60
33	2 x back feet	threaded	5
34	2 x wheel & yolk assembly	2 x 13mm bolt/4 x 8mm bolt	80
35	2 x restraint bracket	4 x 8mm nut	60
36	1 x safety strap	2 x 10mm bolt (already removed)	
37	Bare machine cabinet		

* Drum unit assembly

29-1	Top block unit (concrete balance weight) • 2 x retention spring • 1 x weight clamp plate • 1 x transit bracket	2 x 1/2" nut/bolt	30
29-2	Wiring	9 x direct connect/3 x IDC	20
29-3	Door seal retainer	1 x hexhead (sprung loaded)	30
29-4	Door seal	(stretch-fit)	5
29-5	Thermistor	2 x hexhead	10
29-6	Thermostat	2 x hexhead	10
29-7	Heater element • plastic cover	1 x 10mm nut snap-fit	20
29-8	Drum front plate	15 x clip	40
29-9	Pressure chamber	4 x hexhead	40
29-10	Bottom block unit (concrete balance weight)	2 x 17mm bolt	75
29-11	2 x Suspension rod	2 x 13mm	120
29-12	Spider/Belt Pulley	1 x 20mm nut	20
29-13	Outer drum		
29-14	Inner Drum		

Observations

As an incidental part of this data collection exercise, observations were made on a number of issues, both by disassembling the washing machine and by talking with various company personnel who have an involvement in the machine's life. These are detailed below:

Timer

Initially the company requested that the timer unit be focused upon first. The unit is used widely among the company's range of products and is therefore a high volume generic item. On examination during the disassembly of the machine and from the BOM supplied by the manufacturers, the timer was found to consist of a high variety of low value components. Additionally, the timer proved difficult to disassemble, with complex components of different materials being fixed together in a manner that rendered them impossible for successful disassembly. The timer had to be broken apart, resulting in damage to the outer casing and inner components, making re-use impossible. Additional discussion with the company's service department revealed that timers could not be re-used without inspection to examine internal wear and the oxidisation of contacts. It was therefore decided to assume that the timer unit would not be re-used and instead designated as scrap.

Electric Motor

The motor is relatively easy to recondition, with the armatures being replaced as standard practice. The service department estimated a cost saving of around 50% against the cost of a new motor and a proven failure rate of less than 1%. However, only a small percentage of re-manufactured motors are already used by service as replacement items.

A contentious issue identified was the positioning of the motor in the machine. Some people argued that with the motor at the top of the machine serviceability was easier and life-span increased, due to the drier conditions at the top of the machine; and cheaper wiring. On the other hand, there were arguments for the motor being at the bottom of the machine based on increased stability and hence better operational performance in terms of vibration.

Pump

It was identified that the company currently used six types of pumps in its washing machine production. As a result, such diversity would cause a problem in trying to match demand with supply if they were to be used in a service application. It was found that the quickest way of removing the pumps from the machine was by cutting the hoses.

Drum

The outer drum consists of polypropylene, with a moulded-in metal bearing housing, which is keyed into the outer drum. The metal housing also acts as a heat-sink for the bearing. Hence, there is a balance between achieving a heat reduction in the bearing unit and maintaining the heat of the water in the drum. Such a design results in a lengthy disassembly time. In addition, because the inner drum becomes worn and corroded, it is difficult to separate from the outer one. Therefore the current drum unit design negates effective re-use or recycling.

Safety Interlock

The machine has a safety interlock on its doors, to prevent flooding or harm to the consumer. Traditionally, interlocks worked on a timer principle, however the time-limit was annoying to consumers. Therefore the machine has an interlocking door that works on the basis of a pressure switch in conjunction with a mechanical pulley belt sensor. This interlock design is very complex with a high variety of materials, which makes for poor recycling.

Control Module

The service function estimated that modules could be refurbished with a saving of 30-40% of that of a new module. However, the module designs are frequently upgraded and therefore refurbished modules could not be used effectively in service applications. An opinion was expressed that modular design would aid compatibility of upgraded modules.

Soap Dispenser

The soap dispenser draw is produced from two types of polymers; one that can withstand high temperatures and highly chemical environments; and one that is provided for aesthetic purposes. The draw is presently added to the console back-plate by four screws, with a layer of foam glued between them. This is not desirable from a cost, time or environmental perspective.

Green Chips

A problem with taking back products is to understand the type of use that they have received throughout their life and their configuration. Some machines, which although aesthetically seem to be in a pristine condition, have in fact been subject to heavy usage which reduces the value of components for re-use or refurbishment. Hence, an area of further work required is that of 'green chips' or 'milometer chips' which log information such as the amount of times a machine/component has been used; and importantly the bill of material.

Disassembly Decision Support

The AMDEL computer model has the potential to be used as a daily decision support tool. It models individual disassembly operations; the cost of the operations; the value of any scrap; the cost of refurbishment; and the value of the refurbished component. A graphical plot is made of the cost expended and the value recovered as the machine is disassembled, demonstrating the profitability. By varying the values, costs and precedence of disassembly, different profit profiles can be established. Information could be provided from external and internal sources relating to the current service demand for components and the current prices for scrap material. Hence, the disassembly operation could be optimally managed on a real time basis.

Warranty Costs

If a machine breaks down and is deemed repairable by the service engineer then the company attempts to order replacement parts within 15 days. If the parts cannot be obtained within this time frame the machine is replaced with an exact or similar model at a considerable cost to the company. By accepting more post-use machines from customers in order to use their components in the service/warranty function, such high costs could be avoided.

Eco-label

The AMDEL model did not consider any of the variables that affect the machine during its useful life. A further development of the model could incorporate in-use attributes such as energy and water consumption. A further use of the model could be for an examination of the cost impact on the logistics network of the imposition of a carbon tax.

BEAB Regulations

The company have to ensure that the design and manufacture meets BEAB requirements. All joins and vacant holes in the outer casings of washing machines must have a water sealant applied in order to meet BEAB requirements, however, such sealant is environmentally harmful. Other requirements assist recycling, for instance, all holes drawn in the casings for screws must be able to withstand a minimum of eight re-insertions.

Packaging

The company has a policy of taking back all packaging, once a machine has been delivered directly to the customer. However, in practice only 6% of cardboard and polystyrene packaging is recovered.

Detergent

The company are finding that the new environmentally friendly detergents are becoming more corrosive which could cause problems in the future with the seals on the machines.