Loughborough University

DESIGN AND FINANCIAL ASPECTS OF THE END-OF-LIFE MANAGEMENT OF TELECOMMUNICATIONS PRODUCTS

by

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CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this thesis, that the original work is my own except as specified in acknowledgements or in footnotes, and that neither the thesis nor the original work contained therein has been submitted to this or any other institution for a higher degree.

Dedication

To my father, mother and sister.

Dedication

To my father, mother and sister.

ABSTRACT

As a result of legislation the electronics industry faces product takeback and recycling. It is therefore important to understand the environmental burden caused by discarded consumer electronics and also how to better manage raw materials.

The thesis begins with a review of current environmental issues from the viewpoint of the electronics industry. This shows that there are many complex interactions to be considered within any environmental framework particularly those between legislation, technology and business. Consideration of the drivers indicates that work should focus on the design understanding required to allow product life extension as well as current strategies addressing the reprocessing of used products.

The body of the thesis therefore has two themes, both of which use telecommunications products, telephones, as their exemplar. The first theme, the design issues related to the end-of-life management is explored via a benchmarking study of eight telephones from European (UK and Germany) and Far Eastern suppliers (China and Malaysia). This study allowed the generation of design rules for such products. The work also examined the impact of design changes to improve end-of-life practices on manufacturing costs in Europe and the Pacific Rim to indicate the constraints of labour and investment costs.

The second theme links the business and technological issues faced in the end-of-life (EOL) management of electronic products. The EOL options considered are: resale, remanufacturing, recycling, disposal and to a limited extent, upgrading. Building on the technological understanding generated in the first theme accurate economic models are derived, based on commercial data, for exemplar telephone products that reflect the activities within each option. The potential revenue from each option indicates preferred design strategies and the models can therefore help resolve some of the uncertainties faced by decision makers.

The thesis closes by identifying that the design rules and financial models are particularly appropriate for mature products such as the telephones used as exemplars, further research is therefore necessary to extend the existing work to high added value products.

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NOMENCLATURE

ABS	Acrylonitrile butadiene styrene
AHEA	Japanese Association for Home Electric Appliances
BT	British Telecom
CEN	European Standards Organisation
CFC	Chlorofluorocarbon
CRT	Cathode ray tube
DFA	Design for Assembly
DFDA	Design for Disassembly
DFE	Design for Environment
DFMA	Design for Machine Assembly
DFS	Design for Service or Design for Sustainability
DFX	Design for 'X' where 'X' is a desirable product characteristic such as manufacturability, testability and safety.
DIS	Draft International Standard
EDIP	Environmental Development of Industrial Products programme funded by the Danish Environmental Protection Agency
EMAS	Eco-Management and Audit Scheme
EMPA	Swiss Federal Laboratories for Materials Testing and Research
EOL	End-of-life
EPA	US Environmental Protection Agency
EU	European Union
ICER	UK Industry Council for Electronic Equipment Recycling
ISO	International Organisation for Standardisation
LCA	Life cycle assessment
LCD	Liquid crystal display or Life cycle design
LU	Loughborough University (UK)
MCC	US Microelectronics and Computer Technology Corporation
MITI	Japanese Ministry of International Trade and Industry
MMU	Manchester Metropolitan University (UK)

MOEA	Minnesota Office of Environment Assistance
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OMPAC	Over moulded plastic array carrier
PC	Personal computer
PCB	Printed circuit board
REPA	US Resource and Environmental Profile Analysis
SAGE	Strategic Advisory Group on the Environment
SETAC	Society of Environmental Toxicology and Chemistry
SWICO	Swiss Economic Association of Information, Communication, and Organisation Technology
TAG	Technical Advisory Group
TC	Technical Committee

CHAPTER 1

Introduction

1.0 Introduction

In recent years there has been growing interest in the environmental industry — the production of goods and services used to control, reduce and remediate pollutants — this in turn has led to a growing awareness that going "green" can increase industrial competitiveness and enhance a firm's reputation in the eyes of both customers and public at large. Across the world, company responses to environmental issues have mostly been driven by legislative demands although the emergence of the "green consumer" movement has now created a market pull for cleaner products and processes. Company responses to environmental issues on the whole have been largely reactive. They are often compelled into action following major accidents such as the release of dioxin at Hoffman La Roche's Sevesco plant in Italy in 1976 and the disaster at Union Carbide's plant at Bhopal in India in 1984. In the USA, the shock of the Bhopal disaster stimulated responses in a number of chemical companies such as Dow, Dupont and Monsanto to introduce company-wide programmes to minimise waste and reduce risks.

There have been two noticeable waves of environmental concerns, the first in the early 1970s when some major multinationals such as IBM and Philips introduced corporate environmental polices. The second more vigorous "green" wave was sustained throughout the 1980s and was marked by an increase in the tightening of legislation and public scrutiny on the industrial base. However, it was not until the late 1980s that the concepts of resource conservation and waste minimisation became more widely accepted by both government and industry. This subsequently strengthened the development of "corporate environmentalism"; the emergence of enhanced liability laws and rapidly rising waste costs made waste minimisation programmes increasingly attractive, and also necessary.

In the beginning of this decade, company actions on the environment have been shaped by predominantly regulatory requirements. The initial resistance to fundamental changes both at the product and process levels have resulted in unsystematic end-of-pipe solutions. Diffusion of new ideas and clean technologies has been highly erratic, developing countries often suffer from a weak trickle down of best practise from the developed world. Although end-of-pipe techniques offer a short term and quick-fix solution to pollution problems, wastes have been frequently disposed through dilution, dispersion and landfill, often leading to a transfer of pollution from one medium to another (i.e. from land to sea). However, the re-emergence of the concepts of sustainable development and that of sustainable design in the last few years is seeing a major paradigm shift of environmental management from end-of-pipe approaches towards life cycle approaches. Companies are now beginning to see the benefits of preventing pollution at source instead of their traditional reactive response to pollution problems. Environmental laws are also moving towards a more flexible horizontal nature as opposed to earlier more vertical directives before the adoption of the Masstricht Treaty. These pressures naturally lead to the focus of the thesis.

1.1 The area of investigation

The lack of landfill space, escalating disposal costs and environmental legislation such as "take back" and "polluter pays" have brought the electronics industry the prospect of facing enforced stewardship designed to increase takeback and recycling of electronics products. The focus of the thesis centres around understanding the links between commercial and technological issues that have to be faced in the end-of-life management of electronic products. A chosen number of end-of-life scenarios are considered in this study, these are: resale, remanufacturing, recycling, disposal and to a limited extent, upgrading. Telephones have been used as exemplar products in this work.

Imperative to the understanding of the technological-commercial link requires technological insights into the design issues from the end-of-life perspective as well as identifying the economic drivers behind each potential reprocessing operation. The design understanding has been gained by carrying out a benchmarking case study of eight telephones from European and Far Eastern suppliers with particular emphasis on disassembly, recycling, remanufacture and resale options. Commercial understanding has been developed from a number of factory visits to both equipment manufacturers and recyclers. Design issues examined in the earlier telephone benchmarking study contribute towards the understanding of the process flow in different reprocessing scenarios and help identify economic drivers that constrain each operation. Such constraints are implicit within the derived economic models and the results show the current commercial viability of each processing route.

1.2 Structure of the thesis

Chapter 1 forms the introduction to the thesis and is followed by four other chapters.

Chapter 2 presents a broad review of literature addressing a range of environmental issues with reference to the electronics industry. The five sections contained within chapter 2 are divided into areas of review as follows:

(1) Review of corporate responses to sustainable development and clean technology. This section examines both concepts and draws upon literature that depicts current industrial responses and efforts in strategic approaches to these areas.

(2) Review of environmental and economic drivers in the electronic industry. The first half of this section reviews the various legislative drivers for product takeback and recycling in the electronics industry and examines examples from Europe, Japan and the United States. Various economic factors that drive takeback schemes and the conditions for economically viable operating conditions are further examined in the latter half of the section.

(3) Review of ISO 14000 and Eco-Management and Audit Scheme (EMAS). This section presents an overview to both of these voluntary environmental standards,

outlining the requirements for their accreditation and highlighting the incentives for conformity and potential risks for adopting the standards.

(4) Review of Life cycle assessment (LCA) techniques and their applications in the electronics industry. This section gives a critical review of current LCA practises, examining the limitations of various methodologies within LCA and highlighting some of their applications in the electronics industry.

(5) Design for 'X' - review of design issues in support of sustainable product development. This section examines pertinent Design for 'X' methodologies associated with sustainable product development, where 'X' is a desirable product characteristic such as manufacturability, testability and safety. The particular DFX approaches reviewed here are: Design for environment/ Life cycle design; Design for disassembly and recycling; Design for reuse and remanufacture and Design for service.

Chapter 3 explores design issues related to the end-of-life (EOL) management of products and begins by examining drivers for Design for assembly and disassembly techniques and addressing the conflicting goals between the two methodologies within the current context. The core of the chapter presents a benchmarking case study of eight telephones from European (UK and Germany) and Far Eastern suppliers (China and Malaysia) to establish their suitability for EOL reprocessing. This approach leads to the development of telephone specific rules for EOL processing with particular emphasis on disassembly, recycling and resale options. The impact of design changes of the telephones to improve EOL practises on manufacturing costs in Europe and the Pacific Rim is also examined based on case studies carried out with two companies — one in Malaysia and the other in Wales. The rules developed are also applied to a pager telecommunications device where miniaturised product technology is contrasted with the less technology intensive desktop telephone product.

Building on the understanding of design issues examined in chapter 3, Chapter 4 focuses on the links between the commercial and technological issues that have to be faced in the EOL management of electronic products. The particular EOL stages considered are: resale, remanufacturing, recycling, disposal and to a limited extent, upgrading. Various key variables such as logistical costs, disassembly, reassembly, testing, packaging and parts replacement are identified in each scenario and input to the derivation of economic models matched to current commercial data for a number of telephone models. Sensitivity analyses have been carried out with respect to take back costs and mixtures of EOL strategies. These models help resolve some of the uncertainties currently faced by decision makers and show the commercial viability of each processing route.

The final chapter (chapter 5) presents the author's comments and conclusions on the design and financial aspects of the end-of-life management of telecommunications products, and on the basis of these findings discusses areas for future research.

CHAPTER 2

Literature review

2.0 Review of corporate responses to sustainable development and clean technology

2.0.0 Introduction

The concepts of sustainable development and clean technology are not new but they are receiving increased recognition today. Industrialisation in all countries, developed and developing has proven to be at some cost to public health and the environment. When end-of-pipe pollution controls are added to industrial systems, less immediate damage occurs. Such solutions however are not always proven to be optimal environmentally. Sustainable and clean production provides a comprehensive and preventive approach to environmental protection as it requires investigation of all phases of the manufacturing process and product life cycles.

This section examines the concepts of sustainable development and clean technology and draws upon literature that shows industrial responses and efforts to approach these areas strategically.

2.0.1 Sustainable development

Sustainable development requires a fundamental break from some of the important assumptions and beliefs that have governed traditional development since the beginning of the Industrial Revolution [Davis 91]. Although 70 definitions are now current [Holmberg 92], the widely accepted Bruntland Commission [WCED 87a] defines "Sustainable development is development that meets the needs of the present without comprising the ability of the future generations to meet their own needs". It contains within it two concepts:

- the concept of "needs", in particular the essential needs of the world's poor, to which over-riding priority should be given; and
- the idea of limitations imposed by the state of technology and social organisation on the environment's ability to meet present and future needs [WCED 87b].

The objective of sustainable development can also be described as "improving the quality of human life within the carrying capacity of supporting ecosystems" [MacGillivray 96]. Sustainable development has become more fashionable in the 1990s than in the 1980s although such advanced ideas were raised as early as in the World Conservation Strategy of 1980 which explicitly integrated both development and environment [IUCN 80]. However, the earlier World Conservation Strategy of 1980 reflected a dominantly conservationist environmentalist standpoint and did not address the integration of economics with the environment. This omission perhaps reflected the current political and social setting [Pearce 89]. The rapid progress in environmental concerns in the last decade has increased the understanding of environment-economy interaction; therefore the concept of sustainability has caught on quickly and also fitted nicely into political soundbites. It has been extended from product design, biodiversity to even the ambitious idea of a "sustainable city". Some argue that this view has been carried too far and some economists even object to the whole notion of sustainable development and prefer to think in terms of "optimal" growth of human beings [Pearce 93]. On the other hand, many environmentalists voiced their dislike of the term "sustainable development" as "it appears to license economic growth" [Holmberg 92]. Pearce (an economist) highlights that sustainability should not be an over-riding, single dimension objective for society and that what is "optimal" may not be sustainable (as indicated in the economics literature of the 1970s) and what is sustainable may be simply awful [Pearce 89].

Fundamental to an understanding of sustainable development is the fact that the economy is not separate from the environment in which we live. The interdependence exists because the way we manage the economy impacts on the environment and environmental quality impacts on the performance of the economy. The first type of interaction is straight forward, to illustrate the latter interaction type, the indiscriminate use of chlorofluorocarbons (CFCs) can be considered. That use was, and is, affecting the ozone layer. In turn, damage to the ozone layer affects human health and economic productivity. It is the recognition of the two-way economy-environment interaction as one of the important elements of sustainable development thinking which has led to the evolution of current business ethics and corporate environmental strategies.

2.0.1.1 Corporate responses to sustainable development

Industry is one of the major productive and wealth creating sectors of society. Although it contributes on average one third of measured national income, it is also a major polluter, both directly through its production processes and indirectly through the product it sells. There has been much literature written about how business strategies have begun to address environmental concerns, however, there is a current lack of an integrated, holistic approach on which sustainable business can truly be founded [Hall 96]. Industry might argue that greater environmental protection will be welcomed only when it is affordable. Whilst some companies undoubtedly are making genuine attempts to lead the way in raising environmental standards, many others are making half hearted attempts at exploring the real meaning of sustainability at the corporate level. Due to the lack of overall integrated and holistic approach there appears to be a considerable degree of lip-service being paid to the issue [Enmarch-Williams 96]. As the concept of an "eco-industrial revolution" has only just emerged, the possible scope, timescale and contours of the required changes remain unclear [Robins 95].

Hall et al. [Hall 96] outline three emerging strands of thinking that companies are using to address environmental concerns: (i) compliance strategies (ii) eco-efficiency, and (iii) environmental business strategy. Compliance strategies employed in (i) to address environmental issues are seen largely as a response towards legal and liability concerns. Eco-efficiency mentioned in (ii) is concerned with companies looking for ways to modify their operations to reduce emissions and costs. These strategies are usually based on total quality management principles or building on the principles of environmental management. In environmental business strategy (iii), companies usually experiment with different forms of environmental business strategies that are "borrowed" from appropriate mainstream strategy frameworks that may enable them to integrate environmental concerns across a fuller spectrum of business activities. Hall et al. [Hall 96] present a more detailed review of the different strategic tools that are currently used by firms whilst quantitative tools for environment-quality management are proposed by Madu [Madu 96].

Within a capitalist structure the dominant drive for companies is towards profits and profit maximisation. To succeed in the market place businesses feel the need to cut costs, to downgrade other objectives which might be perceived as expensive, and to cut corners where possible. The emphasis on quantitative measures of performance and on growth has some potential negative consequences. In particular, it tends to push environmental issues down the corporate agenda [Noble 96]. Consequently, there is always an incentive for the profit-maximising firm to become a free rider (assuming everyone else will be environmentally conscious so that one's pollution will be negligible). However, environmental legislation in Western economies is quickly plugging this loop hole and severe penalties are imposed on the offending party. For the free rider, the emphasis on growth becomes all pervading and environmental objectives (which may or may not exist) are compromised. For developing countries, a prime concern has been how to ensure that multinational corporations do not abuse their weak regulatory regimes by operating to double standards [Robins 95]. Multinational companies often have a better environmental record than local companies, mainly because of their visibility to pressure and their superior access to finance, know-how and clean technologies. Consequently, there has been increasing pressure to establish a tough code of conduct for multinationals to provide a basis for minimising the damage done by "free riders" that exploit the differences between the developed and developing world [Robins 95].

Welford [Welford 95] notes that the current trends towards environmental management are often piecemeal and sporadic and brought about by formal and informal pressures from other organisations upon which they depend. This approach does not appear to be consistent with the concept of sustainable development because it does not go far enough in developing strategies to reverse the trend in environmental degradation. This is not helped by the current trend of developing countries to have a proportionately larger industrial sector when compared to the more developed economies such as the OECD which are becoming increasingly dominated by the service sector [Robins 96]. Welford argues that this piecemeal approach is however the accepted ideology because it is being adopted by leading firms, espoused by academics and legitimised by policy makers.

The idea that the involvement and co-operation of industry is key to the drive to achieve sustainable development also presents both opportunities and threats to businesses. For example, "green" consumerism has given environmentally proactive companies the edge in terms of marketing and increased market share. Any industry threatened with dislocation due to shifts in environmental regulation enforcement may find the opportunity to use a technology fix as a possible solution. Technologies that enable countries to exploit their natural reserves more efficiently and cleanly are also avenues that will help create foreign exchange businesses [Rompel 96]. Bird [Bird 96] argues that if a "technofix" is not available, the industry in question may have sufficient power and leverage to obtain a political solution to its problems. He noted examples of industries that may benefit from such trends as the health care sector, the telecommunications industry and the leisure and tourism industry. For companies that ignore the presence of "green" consumerism and continue their operations in an environmentally unfriendly way, declining and heavily regulated markets may be a real prospect and problem.

Trade barriers due to varying global environmental standards could be another potential problem for transfrontier businesses. While internationally active business would prefer that such regulations and standards be harmonised internationally to the maximum extent possible, this will not always be possible, perhaps in some cases not even desirable. Although it is important for governments to develop clear rules and procedures for dealing with the effects of different polices and standards on trade, increasing voluntary efforts by business are a strong lever towards solving the complex environmental challenges and represent a positive step towards enabling a more sustainable environment in the modern industrial society [Morris 93].

2.0.2 Clean technology

Since the late 1980s, the emergence of the sustainable development paradigm has shifted the focus of environmental management from control to prevention, from end-of-pipe to clean technology, in order to achieve a decoupling between economic development and the use of non-renewable resources and related pollution in a process of continuous improvement.

However unlike sustainable development, clean technology has no generally accepted definition. It has been used in the context of source reduction, waste minimisation, cleaner technology as well as clean production [Green 96]. The concept of clean technology goes beyond "clean production" which has been defined by the United Nation Environment Programme [UNEP 89] as "a conceptual and procedural approach to production that demands that all phases of the life cycle of a product or of a process should be addressed with the objective of prevention or minimisation of short and long term risks to human health and to the environment". Jackson [Jackson 93] criticises the focus on production processes rather than embracing redesign of products, and also argues against gradualist notions implied in "cleaner" as opposed to "clean" production. "Clean", he claims, allows for "the expression of a vision of compatible eco-systems". Taking a different viewpoint, Clift and Longley [Clift 95] prefer to see clean technology as an approach to providing services and benefits rather than a recognisable set of technologies. To ensure that a technology is really clean, they stress the need to examine the whole life cycle of the materials or objects which provide the service or benefit. From the environmental point of view, the lack of definitional clarity is not necessarily a weakness, the notion of prevention as the key feature of the clean technology concept is a good starting point, the application of it will depend on which part of the "whole picture" one focuses [Green 96].

In the 1990s, there has been increasing emphasis on manufacturing processes rather than on products and official definitions relating to clean technology have thus been largely centred around processes and waste minimisation [ACOST 92]. The bias towards a process centred definition is partly due to the legislative focus around this area - as depicted by the numerous current international laws governing tighter pollution control and waste minimisation on air, sea and land. For example, Part II of the UK Environment Protection Act of 1990 in waste management imposes a "duty of care" on every person who happens to hold waste along the chain; its producer, transporter and final disposer. It also extends the law prohibiting disposal of waste without a licence to cover not just disposal but also keeping and treating waste; and introduces strict requirements for "after-care" of the disposal site [Mumma 95]. Cleaner production thus encompasses such actions as energy and raw materials conservation, eliminating toxic substances (as raw materials and as product constituents), and reducing the amount of waste and pollutants created by processes and products, thereby lowering the amounts emitted to air, land and water.

2.0.2.1 Waste reduction at source

One of the main shifts in the nature of strategies in the last few years has been towards waste minimisation. In the past, companies saw this as a burden to competitiveness as it entails increased investment in pollution abatement equipment. More recently, heightened environmental concerns and the emergence of stringent environmental laws have created opportunities for businesses to benefit from waste minimisation techniques on the basis of their cost saving potential in conjunction with meeting the challenge of the environment.

The paradigm shift towards prevention and minimisation is also in line with the European Union's policy of the waste management hierarchy: prevention; recycling and re-use; and safe disposal as last resort [SEC 89]. The works of Crittenden and Kolaczkowski [Crittenden 92] and Freeman [Freeman 90] as reviewed by Clift and Longley [Clift 95] suggest that the clean technology approach concentrates on source reduction with some attention also to prompt recycling (see figure 1). Clean strategies would therefore represent a combination of issues concerning input material changes, technological changes, process changes as well as changes at the product level. Each of these will be briefly discussed below.

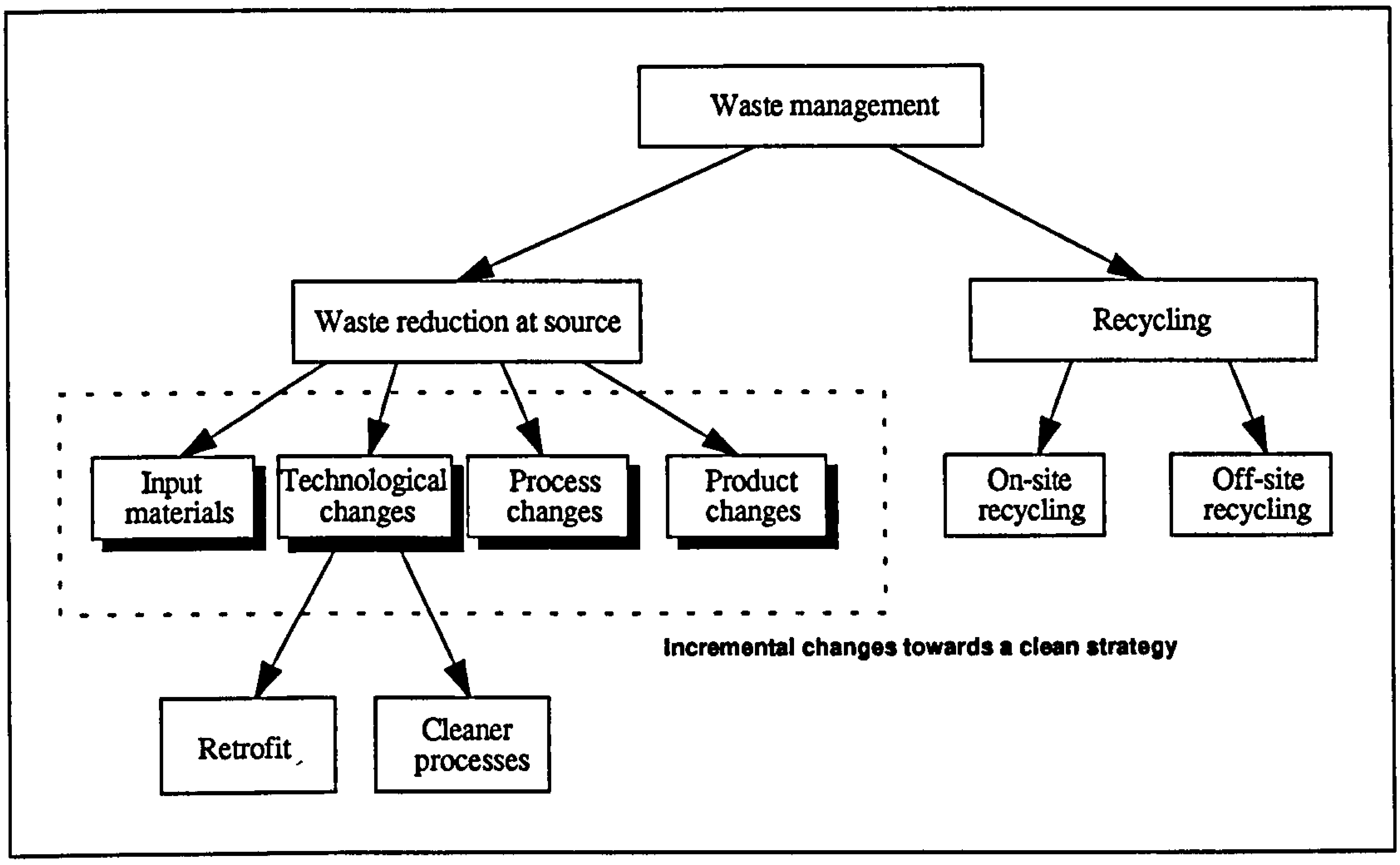

Figure 2.0 Practical techniques for waste minimisation (adapted from Freeman)

2.0.2.2 Input materials changes

Substitution of materials should be considered if it results in reduced environmental loading without compromising the function of the product. This concern particularly addresses the use of toxic substances or chemicals in the manufacturing process. The US Environment Protection Agency's 33/50 programme (a voluntary effort by industrial corporations to reduce emissions of target chemicals relative to 1988 levels by 33% in 1992 and 50% in 1995) is an initiative that drives the potential for materials substitution in products and the potential for process changes. Chlorinated solvents and monoaromatic species comprise most of the items of concern; heavy metals, cyanides (employed in metal plating) and halogenated solvents also appear.

Another consideration for designers in selecting materials is to anticipate future restrictions on materials whose use is not currently constrained. Graedel and Allenby [Graedel 95a] particularly warn against the use of chlorine and chlorinated organic compounds due to their carcinogenic nature. Their abuse may also result in modifications to the endocrine function in both human and animals. However, producers and users defend the undeniable utility of the materials, it is thus unlikely that a comprehensive ban on chlorine containing compounds will ever happen.

It is also anticipated that schemes like eco-labelling and those that are concerned with environmental impact of products over their whole life cycle such as the ISO 14040 (Life cycle assessment) will strengthen the movement towards the use of environmentally benign substances in both design and manufacturing processes.

2.0.2.3 Technological changes

Although the benefits of clean technologies are obvious and the technological know-how available, their adoption so far has been fairly limited. Major investments in end-of-pipe technology in the mid-1980s meant a reduced resource to devote to clean technologies. Although in principle pollution prevention offers a superior solution, many known regulatory standards are still based on the limits of known end-of-pipe technologies [Heaton 94]. Such technologies are usually cheaper, offer far less disruption to the current production process than clean technologies and they give visible proof of the firm's commitment to the environment. Heaton et al. [Heaton 91a] argue that the fundamental impediments to environment-saving technological changes may be attributed to the following:

(i) Goods/ externalities problem. Prices of goods and services do not always reflect the social costs of environmental services. Because users are unable to capture the economic benefits of environmentally preferable technologies, their use is limited.

(ii) Perverse incentives created by governments. Some of these are regulatory while others are fiscal - taxes and subsidies. For example, regulatory product-approval mechanisms that reinforce the current technological *status quo* could delay entry of environmentally superior products. Another example is technology based environmental standards that prescribe design constraints rather than performance requirements can inhibit innovation. High capital cost may be another factor that could restrain the investment in research and development and the replacement of old inefficient capital stock.

(iii) Change is psychologically and politically difficult. New technologies threaten the livelihood of employees and may inconvenience the general public who are accustomed to familiar systems that do not fully integrate environmental factors into their decision-making processes. However, companies that fail to adapt also fail to survive; impediments to technological change are now increasingly driven by the balance of ecological threats with legal and economic drivers [Heaton 91].

2.0.2.4 Process changes

Radical process changes that reduce overall environmental impact are likely to happen only in line with investment cycles [Green 96]. This is due to the risks and associated costs involved in the research and development programme and also in the capital costs that may be invested in the radical redesign of the system. Moreover, companies see process changes in waste minimisation schemes as frequently not associated with environmental gain but rather the potential for cost savings [Johnston 95].

The focus on process change is important as it inevitably leads to changes in the contents of the waste stream itself; current regulatory authorities however place excessive emphasis on emission standards which favour end-of-pipe solutions. There are instances where substitution of an intrinsically clean process for a dirty one may not always be possible. In such cases, "bolt on" systems and "retrofitting" to an existing process to clean up effluent may be required [Davis 91]. Examples are found in metal industries where much of the metal contamination of water occurs.

While incremental innovations in process changes can offer significant gains over time, occasionally more radical process changes can offer large environmental and commercial advantages. For example new biological and inorganic catalysts might improve product yields, cut down by-products, enable less energy intensive reaction conditions by using lower temperature and pressure. New processes can also lead to new products. In the case of the x-ray lithography of silicon microcircuits, it reinforces the "dematerialisation" trend such as miniaturisation and hyperminiaturisation (nanotechnology) where performance of countless industrial functions can be realised with vastly less energy and materials expenditure [Heaton 91b]. The US Semiconductor Association indicates that current technology trends in the electronics industry are not likely to usher in radical changes in the process technology used to manufacture semiconductors throughout this decade [MCC 96a]. The goal however is to refine current processes and use materials that do not impact the environment with zero discharge characteristics. Recommendations for future process refinements at the fabrication level include using lower temperature curing materials (to minimise the overall energy consumption per square millimetre of silicon wafer processed), elimination of oxide treatments in promotion of adhesion, reclamation of etchants, developing alternatives to tin lead etch resists, and the use of aqueous solder masks [MCC 96].

2.0.2.5 Product level changes

Changes at the product level could affect overall waste generation and other environmental loads arising elsewhere in the life cycle. This calls for changes in design approach that emphases reduced environmental impact in manufacturing, use, and final disposal phases. Such changes are normally product specific and commercially sensitive. In this respect, eco-labelling schemes are able to encourage the use of green products without disclosing trade-sensitive information. A generic checklist of potential changes has been suggested by Green and Irwin [Green 96]:

- Consider substituting the materials used with a more environmentally benign one without compromising the design nor function.

- Consider the environmental impacts associated with manufacturing the product at the design stage (i.e. use less manufacturing steps to cut energy consumption).
- Design energy efficient products in the use phase.
- Design products that have reduced environmental impacts at the end-of-life.
- Design for durability. Less frequent replacements mean less disposal frequency.

2.0.3 Conclusions

Sustainable development is a concept that requires individual businesses as well as entire economies to examine their own ethics, objectives and their own forms of organisation, corporate culture and communication. The challenge that faces the environment-economy interaction is how to perpetuate this interaction whilst ensuring sustainability. There is a trade-off between continuous economic growth and the sustainability of the environment and this also implies the acceptance of the view that not all growth and development will be good.

In order to enable development to be sustainable, strategies are needed to translate conceptual theories into practise and there is also currently a lack of an integrated, holistic approach to truly sustainable business. The emphasis to date has been on piecemeal and sporadic moves towards sustainability, although such moves are in the right direction the environment now requires greater urgency and commitment. The move towards clean technology in recent years indicates an attempt to achieve a decoupling between economic development and the use of non-renewable resources and related pollution in a process of continuous improvement.

The paradigm shift towards prevention and waste minimisation is in line with that of cleaner production. However, the concept of the technology goes beyond this and embraces the notion of reduced environmental impact across the entire life cycle of the product. Clean strategies would therefore require a combination of strategic changes at the materials, technological, process and product levels.

Although sustainable development and clean technology deal with issues very much at the macro level, there is likely at some stage in future, to be a fundamental change in the manner which economies are run. Businesses that are perceptive to the fundamental shifts in legislative, economic and social patterns are well placed to exploit green market opportunities whilst those firms unwilling to consider this adjustment may suffer environmental risks such as increased liabilities, greater restrictions on the availability of finance, poor public profile and inefficiency of resource use. These factors may out balance any other possible rewards of business, right down to the "bottom line".

2.1 Review of environmental legislative and economic drivers in the electronics industry

2.1.0 Introduction

The last three decades have seen a sharp growth in the manufacture and sale of business and household consumer electronic appliances. Rapid advances in technology have contributed to the sale of smaller, cheaper and better products. Although the electronics industry has in the past few years injected ecological considerations into the design and overall decision making processes, there are other areas that require continued efforts such as the use of energy, water and environmentally hazardous chemicals. One current issue that has aroused much debate is product takeback. In Europe, Germany, the Netherlands and Sweden have laws pending that would make manufacturers responsible for the ultimate disposal of their products. Other member states of the EU have also shown keen interest. In the Pacific Rim, Japan has also proposed broad takeback projects involving bulky electronics, automobiles and other products. The United States who have been historically behind Europe in takeback policies have begun pilot projects involving voluntary business initiatives.

The first half of the section presents an overview on the various legislative drivers for product takeback and recycling in the electronics industry and will look at particular examples from Europe, Japan and the United States. Various economic factors that drive takeback schemes and the conditions for economically viable operating conditions are further examined in the latter half of the section.

2.1.1 Legislative drivers for product takeback and recycling

It has been estimated that worldwide end-of-life electronic waste stream accounts for only about 2% or less of most municipal waste streams [Martinson 96]. However, policy makers in a significant number of industrialised countries have targeted the electronics industry for particular waste reduction efforts. There are several characteristics of electronic products which have warranted such attention.

Firstly they are bulky, in particular computers and television sets. The size of waste streams of such products have jumped in the past few years due to the high volume of sales and a deep obsolescence curve. Secondly, though equipment may have reached their end-of-life with diminished value add, they can at least theoretically be recovered and component parts be reused and recycled. Thirdly, there are several types of electronic products with high levels of lead and mercury contents and other heavy metals which could leach into groundwater from landfills and hence are environmentally hazardous.

In addition, concerns regarding the lack of landfill space and the subsequent rise in disposal costs have led the electronics industry to the prospect of facing enforced stewardship obligations designed to increase takeback and recycling of electronic products. The impetus towards takeback legislation in the electronic industry according to Davis [Davis 96a], is mainly attributed to the growth of the computer manufacturing industry. In the US, the personal computer (PC) industry accounts for more than a tenth of the gross domestic product. The PC motherboard with its peripheral equipment such as printer, monitor, sound speakers are constantly being replaced about once every five years due to technical obsolescence although they remain fully operational. When considering the number of PCs being replaced globally, the volume of unused products is staggering. This is being reflected in the number of old machines that go into storage once they are traded. American research indicates that up to 75% will go into warehousing, less than 15% into landfill and incineration while only 7% resold and 3% recycled [Martinson 96].

2.1.1.1 European viewpoint

Europe imports between 70-80% of its electronic goods [Ernst 92], the question of takeback could therefore be a major trade issue. However there are trade barrier sensitivities involving the transboundary shipment of electronic waste [Bullock 95]. For example, Denmark and Austria have suggested re-classifying electronic waste from "green" to "amber" under the EU waste shipment regulation [JEC 93], thus allowing transfrontier shipments to be subject to blockage (although both governments see this as an impetus to improve on their national recycling infrastructure). In the US, legislation such as the Resource Conservation and Recovery Act imposes restrictions on the import of hazardous wastes and subsequently led to the increase of the costs of recycling of some materials, such as leaded glass [Davis 96b]. Another potential trade barrier is to use design-based levies which discriminate against foreign manufacturers and put restrictions on transportation that could force manufacturers in overseas markets to set up a recycling plant [Martinson 96].

In Europe, most governments advocating takeback legislation have stated the preference for "voluntary" or "negotiated" agreements with industry. In several countries, the extent in which industry is given the flexibility to work a plausible scheme is debatable. For example in the Netherlands, the government is putting almost the entire responsibility for electronics recycling on the shoulders of manufacturers and importers and have threatened the industry with mandatory takeback. The Dutch government prefers a scheme to be based on "cost internalisation" to make takeback free by incorporating the costs into the price of the new products [Stevels 96]. In Germany, there was an earlier takeback scheme for packaging, however it was mandated with no clear infrastructure. The resulting flood of packaging waste has had to be stockpiled as there was little market. The German officials are therefore being careful to avoid a repeat scenario with takeback of other products. The new Eco-cycle legislation (which took effect in October 1996) allows the government to impose takeback and other obligations on companies selling their products in the country. The Germans are now moving toward a shared-responsibility approach where the end-of-life equipment is to be collected by public authorities and the costs covered in part by household waste charges. Legislation is necessary in order to deter "free riders" that make use of the system without paying for it. In the UK, pilot recovery projects were conducted in 1994 in southern England for electronic waste by the Industry Council for Electronic Equipment Recycling (ICER) to examine the potential for takeback models. Plans are underway to extend the trial to one or two different parts of the UK with different characteristics to understand what volume, type, age and condition of products are being disposed. There is a general consensus against legislation and on the whole the move toward voluntary, industry-led initiatives is being encouraged. As the products collected may not have sufficient intrinsic recycling value, proposals for funding include local authority taxation such as raising current council taxes to fund the recovery and recycling of domestic equipment [ICER 96]. It is anticipated that the UK will also adopt a conservative wait-and-see approach for Europe to move on takeback before a nationwide scheme is established [Snow 95].

Currently there are at least nine European countries moving towards the development of individual schemes for electronic products reaching their end of life. However, despite the European Commission having completed a 18 month project on electronics takeback in 1995, EU legislation on takeback is not yet underway. It is anticipated that any emerging directives are likely to be more horizontal in nature (as opposed to earlier more vertical directives before the adoption of the Masstricht Treaty) to provide greater flexibility for member states to implement them in a manner suitable for local conditions. This is typified in the directives on eco-management and auditing (EMAS), eco-labelling, biotechnology and the waste management strategy [Hull 96]. Should there be any proposals from the European commission, they are not likely to come through before the year 2000. Five core points needed to be addressed at the EU level are [Davis 96c]:

- Common adoption of definitions relating to waste from electronic equipment.

- General principles for organising technical and economic responsibility for dealing with electronics waste to prevent market distortions.
- Targets to be set for each product category to enable environmentally sound, technically and economically feasible solutions.
- What to do with "historic wastes" marketed before the initiatives under current discussion take effect.
- Common EU standards for handling waste to prevent cross-border trade from being distorted by differing national standards that create sharp differences in treatment costs as well as to prevent illegal transfrontier traffic.

2.1.1.2 Japanese efforts

Overall Japanese environmental polices have been very successful in reducing severe industrial pollution which engulfed the cities following the postwar period of industrialisation. However, the tough environmental laws which have led to the current environmental accomplishment did not produce the financial and regulatory burdens that are associated with the German and the American systems. Although this could be attributed to cultural differences where most Japanese firms have a strong social conscience there are however genuine differences in their perception and conduct of environmental issues. In the latter case, local authorities often help shape national environmental policies and have regular open informed technical dialogues with policy makers and firms [Wallace 95a]. This has helped to build a framework that encourages a multilateral flow of information between local and national agencies, individual firms, citizen groups, chambers of commerce, academia and quasi-public research bodies.

The revised Basic Law for Environment of 1993 stems from the Basic Law for Environmental Pollution and Control of 1967 which dealt with environmental standards for air, water and soil, noise levels, vibration, odours and ground subsidence. The major departure of the new law from the old one is that sustainable development formed the basis of the environmental policy creating a legal base for a wider range of policy measures such as education and financial instruments.

One feature of the new law is the framework for voluntary agreements on pollution reduction. Article 8 paragraph 4 states "corporations are responsible for making voluntary efforts to conserve the environment such as reduction of the environmental loads in the course of their business activities" [Wallace 95a]. In the longer term, it is anticipated that current programs on voluntary measures will evolve into a comprehensive framework for reducing industrial pollution. While tackling end-of-life issues, the Japanese Ministry of International Trade and Industry (MITI) in 1996 proposed a broad takeback project involving manufacturers of PCs, automobiles, air conditioners, home electrical appliances and other bulky industrial products with a view to relief the landfill crisis in Japan where landfill space is likely to become extremely limited by the year 2000 [Davis 96d]. MITI has recommended that the Association for Home Electric Appliances (AHEA) establish the Property Disposal Operation Cooperative Center, a recycling consortium to facilitate the transport of collected goods from the retailer to the recycling facility (municipal facility or private recycler). The costs of collecting, transporting and recycling used equipment is split between local authorities, AHEA members (currently consisting of approximately 32 manufacturers of home appliances and 14 industrial associations) and consumers. In general, customers pay a fee upon return of the product to purchase a new one, the manufacturer pays a fee based on product sales and retailers pay transportation costs [MCC 96b].

The electronics industry has begun to address the challenges of future takeback through designs that encourage modular production techniques to allow for easier reuse without full disassembly. Fuji Xerox, Fujitsu, Toshiba and NEC are examples of companies that have started developing a network that collects used products for refurbishing and recycling that are collected mainly from commercial customers [Davis 96d].

2.1.1.3 American efforts

The US regulatory scheme is marked by a breath of complexity that began in the early to mid-1970s when a variety of the now well known "command and control" regulations were passed in the country. Non-compliance is punished quickly and severely due to extensive law enforcement operations. Modern environmental policy in the US is said to have its roots on the first Earth Day (in 1970) and was then closely associated with movements opposed to the Vietnam war thus quickly making environmental politics adversarial [Wallace 95b]. In combination with the generally adversarial working practices of American political, administrative and judicial systems, it is not surprising that the debate about the excessive cost and burden of environmental legislation in the United States appears also to be one of the strongest in the world.

The adversarial, legalistic approach to environmental issues has on the whole produced an inflexible, complicated and often piecemeal regulatory regime. Many regulatory schemes have been developed on a pollutant-specific basis such as air, soil or water. Thus in the course of running a facility, one has to be in command of literally thousands of regulations governing thousands of specific pollutants. The direct consequence of the system has led companies in the United States to build a very costly infrastructure to meet the compliance and remediation requirements imposed by the Environmental Protection Agency (EPA). The former "command and control" approach has nevertheless resulted in very substantial progress in dealing with the major sources of pollutants in the United States; however, this approach is less used now as the focus has moved on to pollution prevention, source reduction and waste minimisation in the past few years [Calland 96]. So far, industrial efforts in these areas have entirely been voluntary, including initiatives on electronic takeback - there are only a few exceptions to voluntary takeback, these being governmental pilot mandatory recovery programs.

Unlike western Europe, the US public has yet to show a similar level of concern towards toxic wastes in the electronic waste stream, such as lead, mercury and other heavy metals [Davis 96d]. The attitude towards old equipment is either to dispose or put them into storage. Takeback also does not at present fall on the agenda of the average consumer. It is been observed that the lag time between Europe's movement on takeback and that of the US allows a learning curve for American companies and policy makers to formulate more strategic solutions from Europe's mistakes [Davis 96d].

Although there are currently no targets imposed on US industry by statute or regulation for takeback, what the US industry is required to do is to certify that it has a programme in place to deal with the problem. A handful of electronics recovery projects have thus far been carried out, such as the one run by the Minnesota county in 1995. The takeback study has resulted in a number of recommendations by the Minnesota Office of Environment Assistance (MOEA) which prohibits the disposal of certain electronic items by 1 January 1997 for businesses and 1 January 1998 for households due to the heavy metal content [MOEA 95]. These items include computers and peripherals, television sets and monitors, copiers, stereo equipment, videocassette recorders, telephones and fax machines.

Another program for electronic wastes recovery began in summer 1996 in Union County, New Jersey and proposals for a self-sustaining electronic processing facility is being scheduled in 1997 for Rhode Island [Davis 96e]. In the former example, Digital Equipment Corporation will be involved in handling some consumer electronics for several of Union County's 21 municipalities with the Union County Utilities Authority (UCUA) overseeing the program. Digital has agreed to collect TVs, microwave ovens, videocassette recorders, home stereos as well as computer equipment with manufacturers AT&T, IBM, Panasonic and Sharp serving as project advisors. In the latter example, start-up funding is through EPA's "Jobs through recycling" program. EPA is soliciting proposals from potential recycling partners to run the facility. Unlike New Jersey, the main goal is to create jobs, this will rely heavily on the program's sound economics.

Table 2.0 summarises the takeback and recycling initiatives in Europe, Japan and the United States.

Country	Key elements	How it is being funded	Status of legislation	Status of other national takeback program
Denmark	•Emphasis on voluntary agreements for producer responsibility. •Industry must decide how to manage electronic scrap.	Disassembly to be funded by customer through end-user fees or surcharges for new products. Municipalities may fund collection.	Legislation will cover any manufacturers not involved with voluntary agreements.	National takeback for tyres is funded by surcharge in new product prices.
European Union	•The "polluter pays" principle and producer responsibility. •A waste management hierarchy (prevention, reuse, materials recovery, energy recovery, incineration and disposal in landfills) No proposed takeback scheme.	Not applicable.	EU's Priority Waste Streams program has suggested that the Commission write flexible framework legislation. No legislation introduced yet.	Not applicable.
France	•Improved recovery rate of electronic scrap. •Elimination of disposal in landfills in 10 years.	Likely an end-user fee.	Two part report, with proposals and goals for minimising electrical scrap, national law expected soon to be based on this.	Not applicable.
Germany	•Government and industry have negotiated three-step takeback decree for electronics. •Industry group CYCLE has proposed its own plan for handling IT equipment.	Government wants industry to repay municipalities for collection; industry favours a mix of end-user fees and higher household waste charges.	Eco-Cycle Law took effect in 7 Oct. 1996. It allows government to impose takeback on industry in general.	Packaging ordinance in 1991.
The Netherlands	•Voluntary producer responsibility plan that sets goals for waste prevention and product recycling.	Government favours schemes based on surcharges on new products.	Landfill ban on electronics is in effect. Government has also threatened electronics industry with mandatory takeback.	Not applicable.

Sweden	Producers and importers to takeback and recycle electronic scrap. Aspects of discussion include: •Ecological and content labelling. •Removing hazardous waste from scrap meant for landfill. •Goals of 85% collection by 2000.	Still under discussion.	Legislation for electronics takeback expected to be approved sometime in 1997.	SWICO program for office equipment and computers has been in operation since 1994.
United Kingdom	•Requirement that recycling be proportional to market demand.	Not applicable.	Government wants electronics industry to establish a voluntary approach.	Not applicable.
Japan	•Law requires government to formulate basic policies for use of recycled materials and to name industries, products and by-products for recycling. •Makers of large household appliances to voluntarily develop recyclable products and design recyclable replacement/ repair parts.	Under discussion.	No legislation for takeback.	MITI proposed broad takeback project involving bulky electronics, automobiles and other products.
United States	•Scattered state and local governments have begun electronic takeback programs. No national takeback scheme has been proposed.	State and local programs likely to be funded by end-user fees.	No legislation.	Not applicable.

Table 2.0 Takeback and recycling initiatives for electronic equipment in Europe, Japan and United States [summary of Davis 96f and Frankel 96]

2.1.2 Economic drivers for takeback and recycling

In general, consumer electronics ranging from portable stereos, television sets to microwaves tend to have low value at their end of life. They lack the valuable components and materials that make disassembly - normally a manual and laborious process- cost effective and worthwhile. A common example cited by electronics industry official as a product being very inefficient to takeback and recycle is the

"Walkman" by Sony Electronics. It is small in size and volume and yields very little material. It is also likely that the labour costs could be more than the value of the product if refurbishment is performed on the Walkman, making end-of-life processing economically unsound.

Of all electronics, computers appear to have one of the highest value at end-of-life [Low 95a]. Their component parts and materials when recovered for reuse, recycled and remanufactured have spun the growth of a secondary industry built around computer equipment which mainly recovers the micro-chips for down cycling applications and precious metal recovery from circuit boards. Incidentally, precious metals are currently employed in much lower proportion in the manufacture of PCBs. Another economic driver that makes end-of-life recovery of computers feasible is their steep obsolescence curve which prompts frequent replacement of the machines. This is important as it provides a sustained feedstock for computer equipment recyclers. The relatively short useful lifespan of computers have also enabled design changes to be made to encourage ease of disassembly, materials separation etc. Design efforts such as using less screws and modular parts are beginning to pay off [Low 95a].

2.1.2.1 Asset recovery

A sound end-of-life economics viewpoint is to turn liability into a revenue stream by continually looking for ways to recover more assets and finding new markets for remanufactured equipment. In recovering an equipment, reuse and remanufacturing are options first considered. The former option requires less energy overall and often offers the highest financial returns especially for computer equipment. The latter option normally requires partial disassembly, fitting of new parts and testing the assembled remanufactured product. Financial returns through this route are also high. Remanufactured "hi-tech" products may be considered obsolete in the original market they are normally sold in developing countries where less modern machines are in demand. However, there are indications in China that although it is the world's largest potential market for refurbished products, selling a refurbished computer could however be difficult as there appears to be a "technology leap" mindset to use only the latest and the fastest. On the other hand, some companies are also reluctant to allow older products to enter the same market as new products as they fear this would affect the sale of their new products.

If the product cannot be reused and sold as a whole system, reusing component parts is next considered. One example would be the sale of recovered integrated circuit (IC) chips from computers - this avenue for business recycler is a fairly new trade which started in 1993. The initial idea was to supply the toy industry with low cost chips recovered from computers. The idea is now expanded to find its use in numerous other applications from garage door openers to smart clocks [Davis 96g]. This has directly led to a flourishing of the second market for used chips and has also helped to drive the toy industry to utilise computer technology cost-effectively.

Two further options for end-of-life recovery are for service parts and materials recycling. In the former instance, spare parts for current service machines often demand high prices and for some companies have even become the primary driver for takeback [Reyes 95]. In the latter case, precious metal recovery in circuit boards has dropped significantly in recent years (150-450 grams of gold per ton in present generation machines versus 400-1400 grams per ton from older equipment) [Biddle 94], plastics are now mainly recovered as they are often the second most valuable material in a computer by weight after precious metals. A large amount of equipment is needed to generate sufficient polymer grades. It has been estimated that the critical mass of 12000 tons of mixed equipment per annum will create 2000 tons of polymer. Within that are 8 to 10 generic types of polymer each one creating, exclusive of colour differences, 10 to 15 differing performance grades [Mann 95]. There are however obstacles to plastics recycling, these include colour matching and material property consistency. The main plastic used in the production of cases in electronic goods is acrylonitrile butadiene styrene (ABS). This material is already recycled, as in the case of telephones and is financially worthwhile [Sarson 92]. Glass recycling from electronic products has been in operation only in the last few years - disposed cathode ray tubes (CRTs) are mainly used as feedstock. The leaded glass contains traces of other materials such as phosphor and aluminium normally making the glass unusable in other contexts. Recycling costs for CRTs is expensive but will decline as the technology improves [Collentro 93, Forrester 93]. It is known that many recyclers give the glass or even the entire CRT assembly to lead smelters as feedstock.

2.1.2.2 Economic risks

A number of risks are associated with taking back electronic products and reprocessing them. Davis outlines these as [Davis 96h]:

(i) Transport and disassembly costs for low value electronics.
(ii) Low volume and quality of returns.
(iii) Challenges provided by some electronics' rapid obsolescence.

In (i), transport overheads appears to the highest overheads associated with takeback of any product type while manual disassembly is also likely to be the norm for the next few years and will thus be cost intensive [Biddle 94]. One of the greatest hurdles manufacturers will have to face is to takeback low value products. However, the intrinsic value of the products are usually not able to self-sustain a takeback scheme and external funding has to be sought. As reviewed in the earlier section, there have been suggestions to "cost internalise" by absorbing future processing costs in the price of the new product or to pay a fee at the product end-of-life. Neither option is attractive to manufacturers as the first may affect sales whilst the second can affect the volume of returns. The future for takeback of low value electronic appears to be problematic, a workable solution would perhaps require drastic measures such as a total landfill ban, higher landfill fees or some other legislative means to force recycling to take place [Davis 96h].

When considering volume and quality of returns in (ii), many recycling businesses prefer to process commercial electronic waste than those from retail consumers. This is because the former is usually "purer" thus possesses higher value and they are normally available in greater volume since most of the products are recovered through leases, rentals and trade-in routes. Another consideration for volume efficiency is to specialise in taking back and reprocessing a reasonable range of products rather than having a takeback scheme that covers a wide variety of products. Wide variety makes it difficult to maximise the recovery value for each unit.

In (iii) rapid obsolescence, particularly in the computer industry, is responsible for industry growth but as discussed earlier is also likely to hasten legislation towards takeback. However, recovery efforts will be most affected as new products with improved functionality may limit reuse value and materials recycling may also be more difficult due to the evolution of more complex materials [Pitts 97]. Consequently, the likelihood of recycling the material for the same application may decrease significantly. Other technological advances such as miniaturisation - as evident in the trend of consumer electronic products will also have a negative impact on the volume of materials being recycled.

2.1.2.3 Managing the takeback schemes

Manufacturers who are considering setting up a takeback scheme have the options of using in-house facilities, a third-party vendor or a combination of both. Decisions will have to be made after weighing the relative merits of each and also having to consider the potential funding sources as well as the products that are most viable to reprocess.

One of the main benefits of using in-house facilities is the control it has over security issues and knowing that the work is being done safely and properly. However, the costs of performing all the refurbishing in-house could be high and time consuming as it entails networking with recyclers, understanding the waste streams and handling the liability of disposal or product warrant issues. Because of such potential problems, some manufacturers prefer using third party recyclers. In doing so, they can leave the job to the expertise of the recyclers and optimise the use of their resources solely in the production arena. As recyclers specialise in their work, they can offer benefits to manufacturers. For example, the recycler may offer better market prices by consolidating materials from several manufacturers. In addition, competition between third party recyclers may force them to upgrade their technology and overall performance, thus putting manufacturers in control of the market. Some manufacturers have also developed a flexible end-of-life management program where a mixed option of using both in-house facilities and outsourcing is employed. Generally, if a third party can provide end-of-life solutions more cost effectively, the manufacturer can outsource the job, otherwise in-house work is performed. There appears to be a trend in the electronics recycling market to move in the direction of outsourcing and the likelihood of using only third party solutions is projected by the year 2005 [Davis 96i].

2.1.3 Conclusions

The experiences to date from the electronics industry in product takeback and recycling show lessons for emerging industrial practises in this area. Europe is probably ahead of the US and Japan because some member States already have mandatory rules. However, some member State governments appear to be more willing to work with industry while others are inclined towards a more authoritarian approach. Although both Japan and the US are currently driven by voluntary systems, industrial responses from both countries indicate active participation in asset recovery both as an image builder as well as to create a learning curve for impending legislation. Unless government and industry are willing to push quickly towards a workable harmonised solution, businesses will have to deal with an international patchwork of takeback schemes that could pose potential trade barriers.

Given the impetuous of legislative drivers to asset recovery, cost effective management of takeback is vital to a company's bottom line especially as the quality and volume of returns are erratic for recovered electronic products. Of all electronics, computers appear to have one of the highest values at end-of-life. When considering the economics of equipment recycling the material value hierarchy is the governing factor. The cost of production resource committed to any operation must be less than the material values achieved. The total process is a delicate balance between commitment and financial result. A third party recycling route is likely to be the favoured route in future although current hurdles for creating a self sustaining takeback program are mainly attributed to funding strategies.

2.2 Review of ISO 14000 and EMAS (Eco-Management and Audit Scheme)

2.2.0 Introduction

The ISO (International Organisation for Standardisation) defines a "standard" as a technical specification available to the public, drawn up with the co-operation and consensus or general approval of all interests affected by it, based on the consolidated results of science, technology and experience, aimed at the promotion of optimum community benefits and approved by a body recognised at the national, regional or international level.

The achievement of standards lends credibility to those organisations that attain them since they provide a basis on which to make comparisons of products and systems between organisations and influence the decisions of customers. An absence of standards on the other hand increases the likelihood of fraudulent reporting and inaccurate claims. In the arena of environmental issues, they provide a credible, self regulatory mechanism to improve performance and demonstrate commitment to environmental stewardship. The objective of environmental standards has been to focus on installing environmental systems that over time will motivate changes to corporate conduct by improving environmental aspects in all areas of decision making. The United Kingdom has been a leader in this area by developing the first internationally accepted standard on the subject, the British Standard 7750 in 1991. The European Eco-Management and Audit Scheme (EMAS) has also been developed in the wake of BS 7750 and these efforts have led to concerns that they may soon be wide spread and function as potential trade barriers. This soon led to an international effort at harmonising impending problems through the International Organisation for Standardisation by developing the first framework for co-ordinating existing environmental management responsibilities.

The two environmental management systems reviewed in this chapter are the ISO 14000 series of environmental protection standards and the European Eco-Management and Audit Scheme (EMAS). The former represents an on going effort on an international basis to define an environmental framework whilst the latter is a more established European based regulation. Both environmental instruments are voluntary in nature and they assess the management capabilities of companies, they are however not concerned with product performance goals.

2.2.1 ISO 14000 environmental protection standard

2.2.1.1 Background

From a historical perspective, in the light of both the rapid adoption and acceptance of the ISO 9000 and the proliferation of environmental standards around the world, ISO began an inquiry in 1991 to assess the need for international environmental standards. This led to the formation of SAGE (Strategic Advisory Group on the Environment) consisting a panel of experts from member countries. In the autumn of 1992, SAGE presented its recommendation to the Technical Board which authorised the formation of Technical Committee 207 to develop the ISO 14000 series. More than 102 countries will vote to adopt the standards, more than 40 of which are "participating" countries and more than a dozen are "observer" countries. Each participating country has working technical advisory groups (TAGs) who will help draft the working documents and oversee the balloting within the participating and observer countries.

The ISO 14000 standards are intentionally modelled after the ISO 9000 series on Quality Management Systems issued in 1987. Part of the reason was to enable a combined environmental and quality management systems audit, since the systems apply the same continuos improvement methodology of total quality management to their respective contexts [McCreary 96]. This harmonisation is likely to have a significant financial impact by offering a joint ISO 9000/ 14000 accreditation option to more than 50 000 companies (as of 1995) registered with the ISO 9000 standards.

The ISO 14000 standards do not in themselves set levels of environmental performance but rather specify the requirements of an environmental management system. They prescribe what should be done by an organisation to manage the impact to the environment of its activities, but do not dictate how to do it. These standards, like other international standards, are not intended to create non-tariff trade barriers or to change an organisation's legal obligations.

Registration of the standards can take from six months to year, and once granted, lasts for three years. The registration is listed in a directory and can be publicly displayed as evidence that conformity to the standard has been achieved. However, registration can also be "disapproved" or made conditional upon performance of specified corrective actions.

2.2.1.2 Outline of standard

The ISO 14000 is a "voluntary" standard with generic standards divided into two basic types: Guidance and Specification. The former documents are non prescriptive whilst the latter are mandatory documents. The only *specification* document is the ISO 14001 ("1996 Environmental management systems - Specification with guidance for use") while the remaining documents (14004, 14010, 14011, 14012) are *guidance*. This means that company seeking participation in the ISO 14000 which in itself although voluntary, will have to conform to the ISO 14001 *specification* while using the rest of the relevant standards as *guidance*.

As the time of writing, the following have been formally adopted as international standards:

Standard	Description
ISO 14001	1996 Environmental management systems - Specifications with guidance for use
ISO 14004	1996 Environmental management systems - General guidelines on principles, systems and supporting techniques
ISO 14010	1996 Environmental management auditing - General principles

ISO 14011	1996 Environmental management auditing - Auditing procedures - Auditing of environmental management systems
ISO 14012	1996 Environmental management auditing - Qualification criteria claims - Guidelines and definition and usage of terms

The following are draft international standards (DIS) but shall be adopted as official standards following international balloting. DISs are also eligible for adoption as national standards while balloting is taking place.

Draft Standard	Description
ISO/DIS 14021	Environmental labels and declarations - Self declaration environmental claims - Guidelines and definition and usage of terms
ISO/DIS 14040	Environmental management - Life cycle assessment - Principles and framework
ISO/DIS 14050	Environmental management - Vocabulary

In addition, TC 207 is developing other documents that have not yet advanced to the DIS stage. These are:

Draft Standard	Description
ISO/Draft 14024	Environmental labelling - Practitioner programs - Guiding principles, Practices, and Certification procedures of multiple criteria (type 1) programs.
ISO/Draft 14031	Environmental management - Environmental performance evaluation. Expected to be completed in 1998.

There are various other work items at various stages of completion under the ISO 14000 series. Some may not be completed before the year 2000 while others may be eliminated or combined with other activities, depending on whether there is justification to retain the work items.

2.2.1.3 Benefits of conformity with ISO 14000

A single international standard will avoid multiple registrations, inspections, and certifications and will provide a single system for multinational companies to implement wherever they choose to operate. International management standards offer a number of advantages over the proliferation of national and regional standards. These latter types of standards create unnecessary costs for organisations while raising potential barriers to international trade. One such example is the EU's eco-labelling regulation. If applied strictly, these requirements have the potential to exclude most manufacturers in developing countries from qualifying for the EU's eco-label.

Although the ISO 14000 is a voluntary standard, there are a number of market forces that may impel a company to conform to the standard. One of which may be imposed as a requirement for doing business as in the event of a company adopting the ISO 14001, its suppliers, contractors and vendors may also be required to adopt the same standard. If the company is a large one, the market incentives, even to smaller domestic companies could be significant.

Companies may use the standards to help manage and maintain their regulatory compliance status with the regulatory agencies or to repair any possible prior negative publicity from previous enforcement actions. In the USA where the environmental regulatory burden is between 3% and 8% of the gross national product [P2AD 95], various environmental protection agencies (EPA) and Department of Justice policies promote comprehensive environmental auditing as a means of mitigating penalties and diminishing the likelihood of criminal referrals or regulatory inspections.

The standards may, in some countries obviate the need for certain regulatory "command and control" initiatives and may help to level the competitive global environmental playing field by establishing an internationally recognised minimum "floor" standard for environmental management.

Perhaps, most importantly, the ISO 14000 offers a co-ordinated framework that helps environmental managers perform existing responsibilities such as reduction of housekeeping, reporting and monetary fines against companies. It also promotes lasting systematic changes in corporate management systems since the standards encourage proactive planning for environmental aspects in executive decision making, leading to potential changes in the corporate culture. From a marketing standpoint, it will project the credibility of the company's commitment to sustained environmental stewardship to their shareholders as well as customers. An enhanced image and product recognition is also likely to access more markets. In the manufacturing operations, an effective implementation will lead to better cost control, more efficient management of resources and reduce potential liabilities. Liability limitation is also likely to lower insurance costs.

2.2.1.4 Potential risks

However, there are also risks involved in the participation of the ISO 14000 and this appears to be more of a legal concern in the USA than internationally as most environmental compliance requirements in America are enforceable criminally. Third party audits (which is a prerequisite to the registration of ISO 14001) may reveal that a company may not be in compliance with an EPA rule which when reported could lead to significant fines. The role of the auditor appears to be in conflict in this instance. Technically, regulatory compliance is outside the scope of the audit, however ISO 14001 requires compliance with regulatory requirements [Sissel 95]. One solution is to perform an "initial review" preferably under the attorney-client privilege to ensure that the documentation generated does not expose the company to regulatory enforcement or third part citizens suit liability [McCreary 96].

The trustworthiness of third party firms that inspect and certify facilities is also an important element. In the USA, competing sets of criteria have emerged for accrediting certifiers and organisations are cautious not to fall within the early stages of a new certifier's learning curve [Begley 96]. This concern was echoed by environmental groups about giving important regulatory functions to private sector companies that may be ill qualified and yet do not have visibility to the public.

Although recent surveys indicated there is a general high regard for ISO 14000 by the industry, the new standard is criticised in that it only shows that companies are addressing the appropriate issues in their environmental management standards but does not actually highlight anything with regard to actual performance - the kind of improvements Responsible Care* intends to communicate to the public [Sissel 95]. The combined audit of ISO 14000 and ISO 9000 was also greeted with much scepticism. It could be argued that while quality programs address the need of the customers, environmental programs mainly target the concerns of regulators and the public and both have very different stakeholders in each of the management areas. It may be inappropriate to combine the two management systems into a single system of auditing. Perhaps the only real shared area is the documentation [Lawrence 96].

Another potential risk of the ISO 14000 is being over optimistic about market influences on the registration of the standard. As ISO 9000 has proved to be a costly adventure to some companies, some argued that the ISO 14000 appears to be just a compliance instrument and offers very little value added [Pouliout 96]. The wait and see attitude adopted by companies in part reflect the concerns regarding the expense (based on their ISO 9000 experience) and in part due to the availability of domestic registrars and certifiers.

2.2.1.5 Overview of ISO 14000 series documents

The initial version of the ISO 14000 will consist of standards related to the following items:

- Environmental management systems
- Environmental auditing
- Environmental performance evaluation
- Life cycle assessment
- Environmental labelling
- Environmental aspects in product standards

Figure 2.1 depicts the overall structure of the ISO 14000. A brief description for each element of the standard is offered below.

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*Responsible Care is an umbrella scheme started by the Canadian Chemical Producers' Association in the late 1970s. It is concerned with performance (not public relations) and designed to improve performance and demonstrate improvements taking place. The scheme has since been adopted by industry associations in Australia, Europe and the USA.

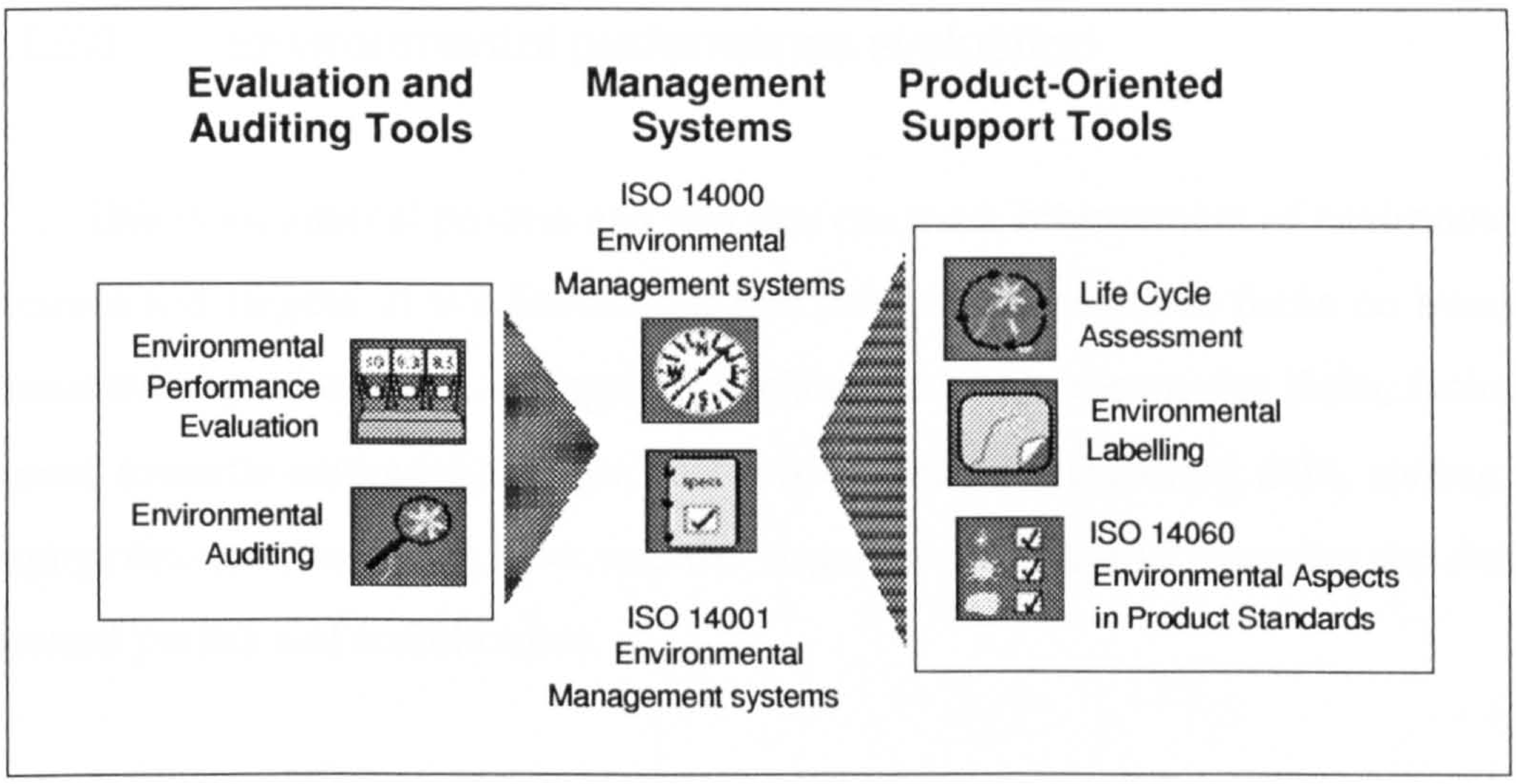

Figure 2.1 Overview structure of ISO 14000 [adapted from Stoller 95]

2.2.1.5.1 Environmental management systems

The ISO 14001 is the fundamental document, compliance with this "specification" document is mandatory. The key elements include: policies and procedures, planning, program management, review and evaluation, management information systems, budgeting and scheduling, communication, legal and regulatory, risk and loss management. The goal of the standard is to provide organisations with an effective environmental management system that can be integrated with other management requirements. It applies to all sizes of organisations across geographic, cultural and social conditions.

2.2.1.5.2 Environmental auditing

The environmental auditing standards provide requirements for general principles of environmental auditing, guidelines for auditing environmental management systems, and qualification criteria for environmental auditors. It is expected that individuals will be able to become certified lead environmental auditors in much the same way as ISO 9000 lead auditors but with specific knowledge and experience in environmental operations, regulations, and technologies.

2.2.1.5.3 Environmental performance evaluation

This is an internal process and tool that can track achievement of environmental objectives and targets. It is a framework that helps management to focus on trends in environmental performance, changes in performance and reasons for them, including progress towards continual change. This process includes gathering data, sorting and grouping the data, assessing how well the targets were met, and reporting the data to interested parties and stakeholders.

2.2.1.5.4 Life cycle assessment

Life cycle assessment* is a means to understand, control and reduce potential environmental impacts of the provision of goods and services from the "cradle to grave" of a product. The key elements of such an assessment include: inventory data input and output analysis of the production process, identifying the most significant environmental aspects that can be controlled, assessing the impacts and suggesting the necessary improvements to be made. It is anticipated that the results from the life cycle assessment will contribute towards environmental labelling as well as the environmental aspects in product standard.

2.2.1.5.5 Environmental labelling

It is used to inform consumers that a third party has certified the product to meet a set of defined criteria that are considered to promote environmentally sound purchasing decisions. The object of the standard is to support third party environmental labelling programs to ensure that they are non-discriminatory, credible, and do not set up trade barriers. The process include provision for transparency of the development of the program, adoption of a "life cycle" approach, periodic review, consultation with stake holders, consideration of product attributes as well as protection of proprietary information.

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*The broader context of LCA is discussed at length in section 2.3.

2.2.1.5.6 Environmental aspects in product standards

This standard is intended to create awareness towards product design provisions that can affect the environment and recommends the use of life cycle thinking and scientific methodologies in developing product standards that incorporate environmental aspects. The standard also encourages development of strategies for improving environmental performance which include resource conservation, pollution prevention and "design for environment".

2.2.2 Eco-Management and Audit Scheme (EMAS)

2.2.2.1 Background

EMAS (full title: Council Regulation No 1836/93 of 29 June 1993 allowing voluntary participation by companies in the industrial sector in a community eco-management and audit scheme) is an EU regulation applying to all 12 member states which came into force in July 1993. This has been developed in the wake of BS 7750 and represents the second market based tool that has been developed by the EU for improving environmental performance and awareness, the first being the Eco-label which was applied to products in 1992 [Sands 95].

EMAS is initially targeted at Europe's industrial sites, however in the UK, the scheme has been extended to include local authorities [EMAS, UKDoE 95]. In the original draft of the Regulation in 1990 the proposal was for a mandatory scheme, but this was dismissed after consultation with member states. The overall objective was to "provide recognition for those companies who have established a programme of positive action to protect the environment, and who seek continuously to improve their performance in this respect" [Sands 95].

Similar to the ISO 14001 standard, EMAS is "voluntary" and does not embrace a "command and control" approach. However, it requires an environmental policy to be in existence within the organisation fully supported by senior management, and outlining the policies to staff, general public and other stake holders. The environmental statement is to be made public and should contain quantifiable data on current emissions and environmental effects emanating from the site, waste generated, raw materials utilised, energy and water resources consumed, and any other environmental aspect that may relate to operations on the site.

2.2.2.2 Outline of standard

The following are the principal components of EMAS that are required to be implemented in order to register for the scheme:

- Environmental policy
- Environmental review
- Environmental programme
- Environmental management system
- Environmental audit cycle
- Environmental statement
- Validation

Figure 2.2 depicts the overall structure of EMAS. A brief description for each of the elements of the standard is offered below.

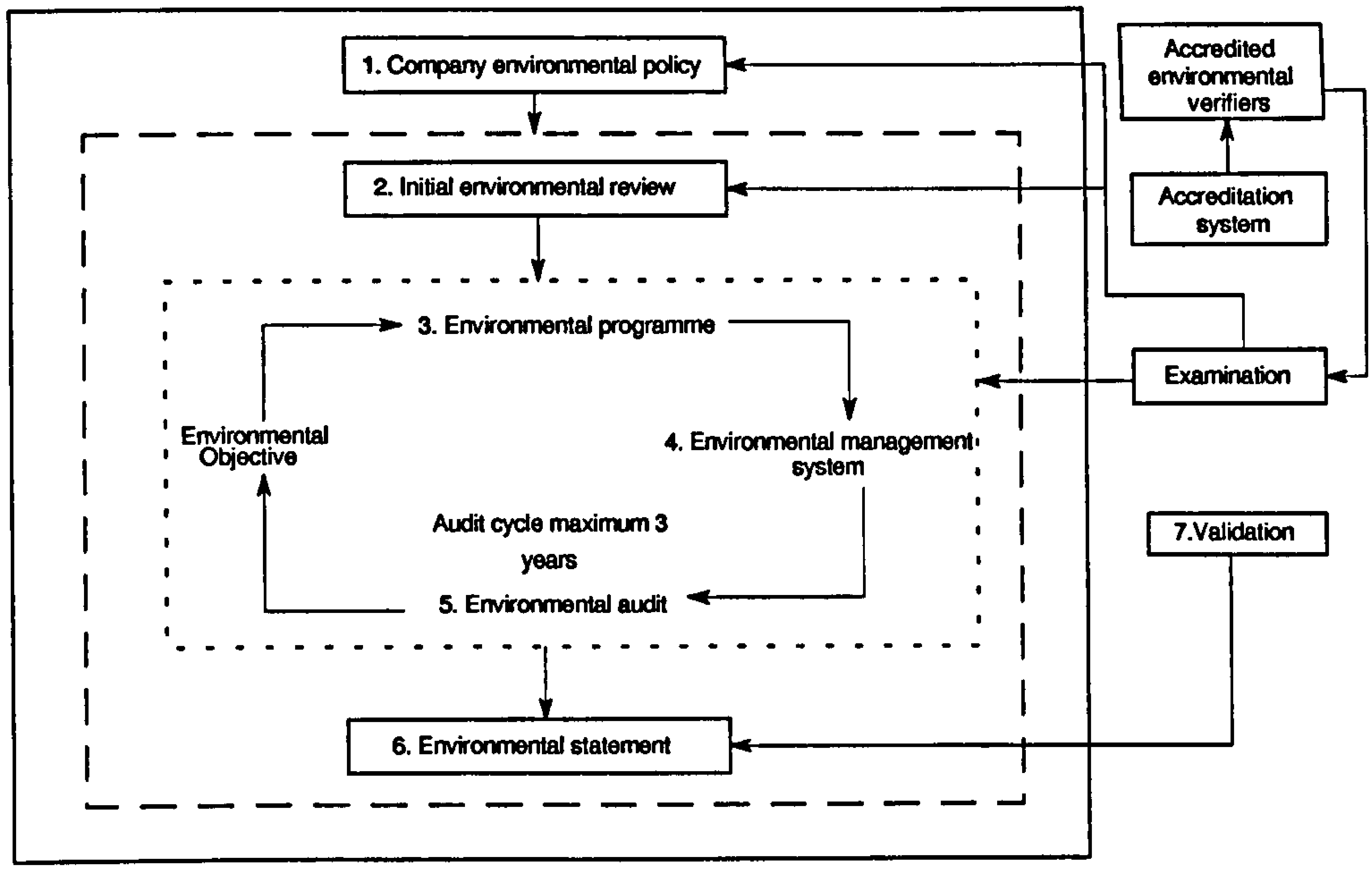

Figure 2.2 Overview structure of EMAS [UK DoE 95]

2.2.2.2.1 Environmental policy

The policy is written and adopted by the highest managerial level and should be communicated to the staff, general public and other stakeholders. The main elements of the policy are: (i) compliance with relevant environmental regulations (ii) a commitment to continuous improvement.

2.2.2.2.2 Environmental review

This will consist a detailed analysis of the relevant environmental impacts and issues for the management which encompass aspects such as energy, raw materials and waste management, noise control and current accident procedures. All the environmental legislation applicable to the site are required to be listed and whether any of them are being violated.

2.2.2.2.3 Environmental programme

The environmental programme describes the objectives and the activities of the site designed to ensure greater protection of the environment and includes description of the measures taken or envisaged and the dead lines set for the implementation. This should be set out in accordance with the policy and review.

2.2.2.2.4 Environmental management system

It is the mechanism which ensures that the authority not only adopts environmental polices but also carries them out. The main features are: (i) identifying the people for carrying out the responsibilities for the particular actions (ii) setting up the procedures for doing these things (iii) develop a mechanism for recording environmental actions.

2.2.2.2.5 Environmental audit cycle

The purpose of the audit is to scrutinise and evaluate environmental performance which is checked against the stated policy, goals and regulations and to make recommendations for improvement. The frequency of the full audit cycle will depend on the nature and risks associated with activities on the site but must take place at least every three years.

2.2.2.2.6 Environmental statement

It is a document that should provide the public with sufficient information on the environmental performance of the site to enable it to exercise effective public scrutiny. A statement is produced after the completion of each audit and must be concise and comprehensible and of a form and length to be read by ordinary members of the public. It is essentially the same kind of document as the annual environmental reports that some companies already produce.

2.2.2.2.7 Validation

This is the stage in which the activities of the site are checked by an independent, accredited environmental verifier to ensure that they meet the requirements of the scheme. The process will involve: examination of the documentation, visit(s) to the site and interviews with personnel and preparation of a report to the local authority including identification of any problems. If the systems on site are already certified to BS 7750, EMAS requirements are automatically met [EMAS, UKDoE 95].

2.2.2.3 EMAS's relationship to ISO 14000

The more recent ISO 14000 standard was developed with a significant overlap with the Eco-Management and Audit scheme as well as the BS 7750. Conformity with these two widely environmental management standards has initiated strong efforts (developed around a body of EMAS and BS 7750 expertise) to base ISO 14000 on the same principles of sustainable development initially announced by the International Chamber of Commerce [McCreary 96].

Companies that were earlier registered with EMAS or BS 7750 are now interested in whether the EU will also recognise an ISO 14000 registration. Concerns were raised to whether registration with one programme will satisfy all three considering the cost factors involved in participating in all three programmes. Following the ISO TC207 meeting in Oslo in June 1995, an agreement has been reached for the European Standards Organisation (CEN) to adopt ISO 14000 as an acceptable means of implementing EMAS. "Bridging" documents will incorporate certain mandates from EMAS not found in ISO 14000 such as the public disclosure of an environmental statement. However, the concept of a bridging document creates a plausible "international standard" that removes national and regional variations that could be used to inhibit free trade [McCreary 96].

2.3 Review of Life cycle assessment techniques and examples of their applications in the electronics industry

2.3.0 Introduction

Life cycle assessment methods have been in development for over two decades. However trends in more stringent environmental legislation, consumer preference for green products and the potential competitive advantage of companies with a greener image have accelerated research into LCA especially in the last 5 years. Some of the most promising applications are being used internally by corporations and regulatory agencies - they help to scrutinise both the "upstream" and "downstream" of a particular activity, integrating its use in current strategic decision making processes. This section gives an overview of current LCA practises, examining the limitations of various methodologies within LCA and highlighting some of their applications in the electronics industry.

2.3.1 Life cycle assessment history

Life cycle assessment has been in development for well over 20 years with the first international report dating back to the seventies. Life cycle inventory analysis - LCA's predecessor had its beginnings even as early as in the 1960s. Harold Smith at the World Energy Conference in 1963 submitted his findings on the cumulative energy requirements for the production of chemical intermediates and products [SETAC 91a]. In 1969, Coca-Cola initiated a study to compare different beverage containers to determine which one had the lowest releases to the environment and least affect the supply of natural resources. The outcome was the establishment of current methods of life cycle inventory analysis in the USA. Other companies in both United States and Europe also began to do comparative life cycle inventory analysis in the early 1970s. In Europe, the Swiss claims to be at the forefront in the development of modern LCA concepts [Schaltegger 96b].

The process of quantifying the resource use and environmental releases of products was known as Ecobalance in Europe and Resource and Environmental Profile

Analysis (REPA) in the United States; many REPAs were formed in the US in response to the years of oil shortages in the early 1970s. From 1975 to the early 1980s, interest in comprehensive studies began to wane when the oil crisis faded, environmental concern was then shifted to issues of hazardous waste management. During this time, European interest grew with the establishment of an Environment Directorate (DG XI) by the European Commission. LCA approaches were being developed with its first applications toward packaging of beverages - a comparative study was performed for both disposable packaging and returnable packaging [EPA 93a].

In 1985 DG XI issued the Liquid Food Container Directive, which charged member companies with monitoring the energy and raw materials consumption and solid waste generation of liquid food containers. When solid waste became a worldwide issue in 1988, the life cycle inventory analysis technique again emerged as a tool for analysing environmental problems. Interest in moving beyond the inventory to analysing the impacts of environmental resource requirements and emissions gave birth to current LCA concepts and practises. The Society of Environmental Toxicology and Chemistry (SETAC) has since served as a focal point for technical developments in the life cycle assessment arena. The incorporation of LCA into the recent ISO 14000 standards once again indicate the methodology as a credible tool as part of environmental management.

2.3.2 Components of Life cycle assessment stages

Life cycle assessment is a tool to evaluate the environmental consequence or activity of a product holistically across its entire life. SETAC defines the life cycle stages addressed in an LCA to include raw materials acquisition, manufacturing, use/reuse/maintenance, recycling and final disposal [SETAC 93a]. LCA identifies inputs and outputs; assessing the potential impacts of those inputs and outputs on ecosystems, human health, and natural resources; to provide decision makers with information which defines the environmental effects of these activities and identifies opportunities for achieving improvements.

The four interrelated components of an LCA* are: (i) Goal definition and scoping (ii) Inventory analysis (iii) Impact assessment, and (iv) Improvement assessment. Figure 2.3 illustrates this relationship. A brief summary for each stage considered in the LCA is given below.

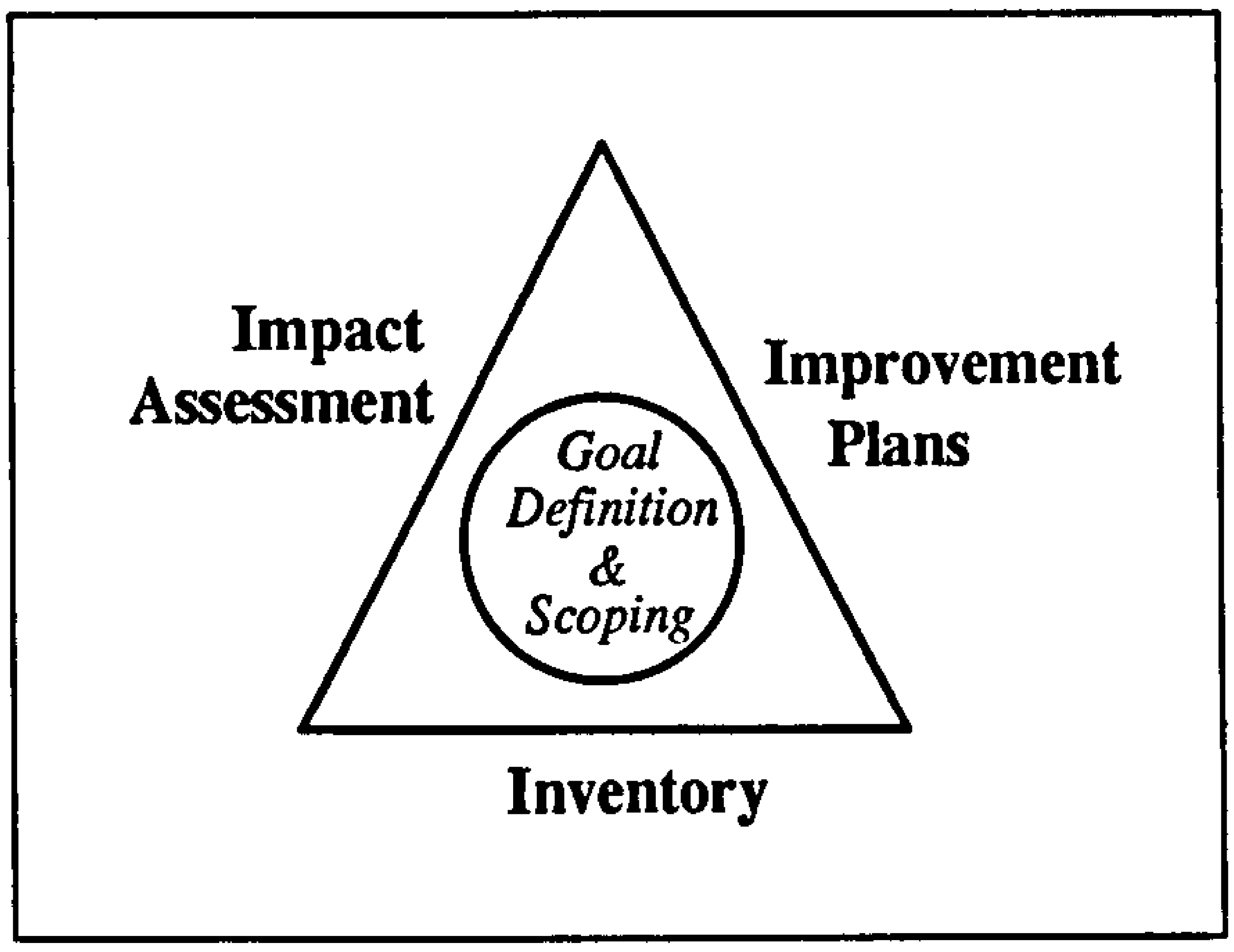

Figure 2.3 Life cycle assessment framework

2.3.2.1 Goal definition and scoping

During goal definition, the product, process, or activity is defined for the context in which the assessment is made. It is often considered the most critical component of an LCA as it determines what will or will not be included in the study pertaining to boundary setting, data categories and data needs. A major consideration is whether the results will be used for internal company applications or externally, for example, to influence public policy.

In scoping the LCA, it is important that all boundaries, methodology, data categories, and assumptions be clearly stated, comprehensible and visible. These include geographic extent (local, national, global) and the time horizon (product life, impacts of processes). For internal life cycle inventories, scoping may be done informally by project staff. Scoping for external studies may require the establishment of a multi-organisational group and a formal procedure for reviewing the study

*This is the methodological framework recommended by the Society of Environmental Toxicology and Chemistry (SETAC).

boundaries and methodology. It may be necessary to re-evaluate the scope periodically during an LCA.

2.3.2.2 Inventory analysis

Inventory analysis is the most established component of LCA. Studies have been undertaken by Boustead, Franklin Associates (both working for over two decades) and others such as Chem systems, National Institute of Standards and Technology (USA), Battelle and Arthur D. Little [Brinkley 94]. Both the US Environmental Protection Agency (EPA) [EPA 93a] and SETAC [SETAC 91a] have developed guideline documents which highlight the following activities in a life cycle inventory:

- **Defining the purpose and scope of the inventory.** Considerations should be given whether it is for private/ public sector use. The level of specificity must also be decided to determine if a generic study is to be undertaken or one that is product specific in every detail.

- **Defining the system boundary.** The subsystem boundaries are outlined in figure 2.4 which divides a life cycle into four major stages: raw materials acquisition, manufacturing, use/ reuse/ maintenance, and recycle/ waste management. Viewing the steps as subsystems facilitates data gathering for the inventory system as a whole. Depending on the goal of the study, it may be possible to exclude certain stages or activities and still address the issues for which the life cycle inventory is being performed. US EPA guidelines suggest that only when a step is exactly the same in process, materials and quantity in all alternatives considered, can the step be excluded from the system - a rule which is critical for inventories used in public forums rather than for internal company decision making [EPA 93b]. In an inventory analysis, defining a baseline for future product development/ improvement is important, it is the unit upon which the analysis is performed and can be almost anything that produces internally consistent data. The analyst must therefore determine the basis of comparison between the systems under examination.

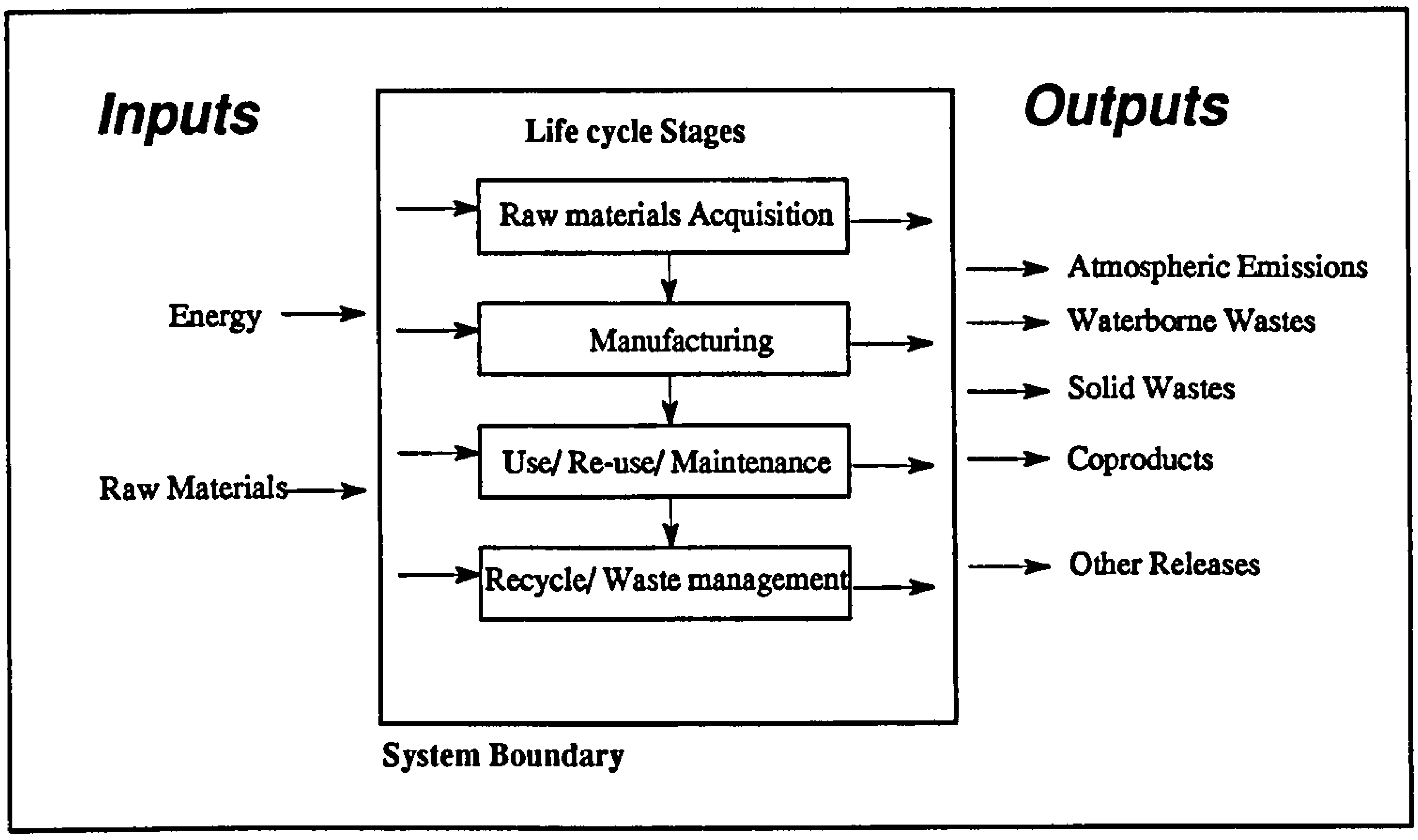

Figure 2.4 Defining the system boundaries for life cycle inventory

- **Devising an inventory checklist.** US EPA suggests eight general decision areas that should be addressed on the checklist [EPA 93b]: (i) Purpose of the inventory (ii) System boundaries (iii) Geographic scope (iv) Types of data used (v) Data collection and synthesis procedures (vi) Data quality measured (vii) Computational model construction (viii) Presentation of results.

- **Instituting a peer review process.** SETAC recommends that the reviewers should have no stake in the report, be technically qualified and that a third "disinterested party" should check the reviewers' comments to have adequately addressed the issues in the inventory model [SETAC 91b]. The peer review has been the focus of many discussions in LCA forums which stems from concerns in four areas: lack of understanding regarding the methodology used or the scope of the study, desire to verify data and the analyst's compilations of data, questioning key assumptions and the overall results, and communication of results.

- **Data gathering.** Data collected for an inventory should always be associated with a quality measure. The analyst should consider the date, source, specificity and relevance of the data. However, the use of proprietary data is a critical issue in inventories conducted for external use and whenever facility-specific data are obtained from external suppliers for internal studies. As a consequence, current studies often contain insufficient source and documentation data to permit technically sound external review. Some form of selective confidentiality agreements as well as formalisation of peer review procedures will be necessary for inventories that are used in public forums. Although current procedures allow data to be gathered, assessed and maintained, their application appears to be lacking in uniformity. In trying to compensate for data gaps, practitioners should be very cautious in their conclusions. Thus, there is a need to develop more systematic, scientifically valid methodologies for characterising and maintaining data quality which are consistent within the goal of any particular study [SETAC 94a].

- **Interpreting and communicating the results.** This will be dependent on the purpose for which the analysis is performed. The boundaries and data for many internal LCA may require the interpretation of results for use within a particular corporation - data used may be specific to a particular company and therefore may not represent any typical/ average product on the market. The public sometimes receives interpreted information from LCA that have been released. In such instances, the analyst must be careful to provide an interpretative context and not to selectively use information.

The various applications of an inventory analysis will include:

- Supporting broad environmental assessments
- Establishing baseline information
- Rank the relative contribution of individual steps or processes
- Identify data gaps
- Support regulatory policies
- Support product certification

- Provide education for use in decision making

The last three applications are most prone to mis-interpretation [EPA 93c]. This is partly due to their more probable use external to the performing organisation and partly due to their implicit orientation towards assessing the environmental consequences of a product or process.

2.3.2.3 Impact assessment

In the impact assessment, the inputs and outputs identified in the inventory analysis are translated into a quantitative and/ or qualitative process for identifying, characterising, and valuing potential impacts to human health, ecosystems, and natural resources associated with a product or process life cycle. Unlike inventory analysis, impact assessment is still not fully developed. Because of the inherent complexities and data requirements of impact assessment, very few LCAs have attempted to include impacts. Currently, there is no consensus on the types of impact models appropriate for use in LCA.

Following a SETAC workshop in 1993 [SETAC 93b], a conceptual framework for life cycle impact assessment was proposed (see figure 2.5), subdividing impacts into Classification, Characterisation, Normalisation and Valuation sections. The classification into problem types (i.e. Human health, Ecological health, Resource depletion) is depicted in figure 2.5. The problem of which environmental impacts to consider in the impact assessment has been the subject of many discussions and many lists have been suggested. There are however common strands between them. As an example, the Danish EDIP method classifies the impact categories into global (global warming, ozone depletion), regional (acidification, eutrophication, photochemical ozone, persistent toxicity), and local (human toxicity, ecotoxicity and area disruption) impacts [Wenzel 94].

Referring to figure 2.5, the key concept in an impact analysis is that of *stressors*. The stressor concept links the inventory and impact analysis by associated resource consumption/ releases documented in the inventory with potential impacts. Thus, a stressor is a set of conditions that may lead to an impact. Life cycle impact analysis does not necessarily attempt to quantify any specific actual impacts associated with a product or process. Instead, it seeks to establish a linkage between the product or process life cycle and potential impacts.

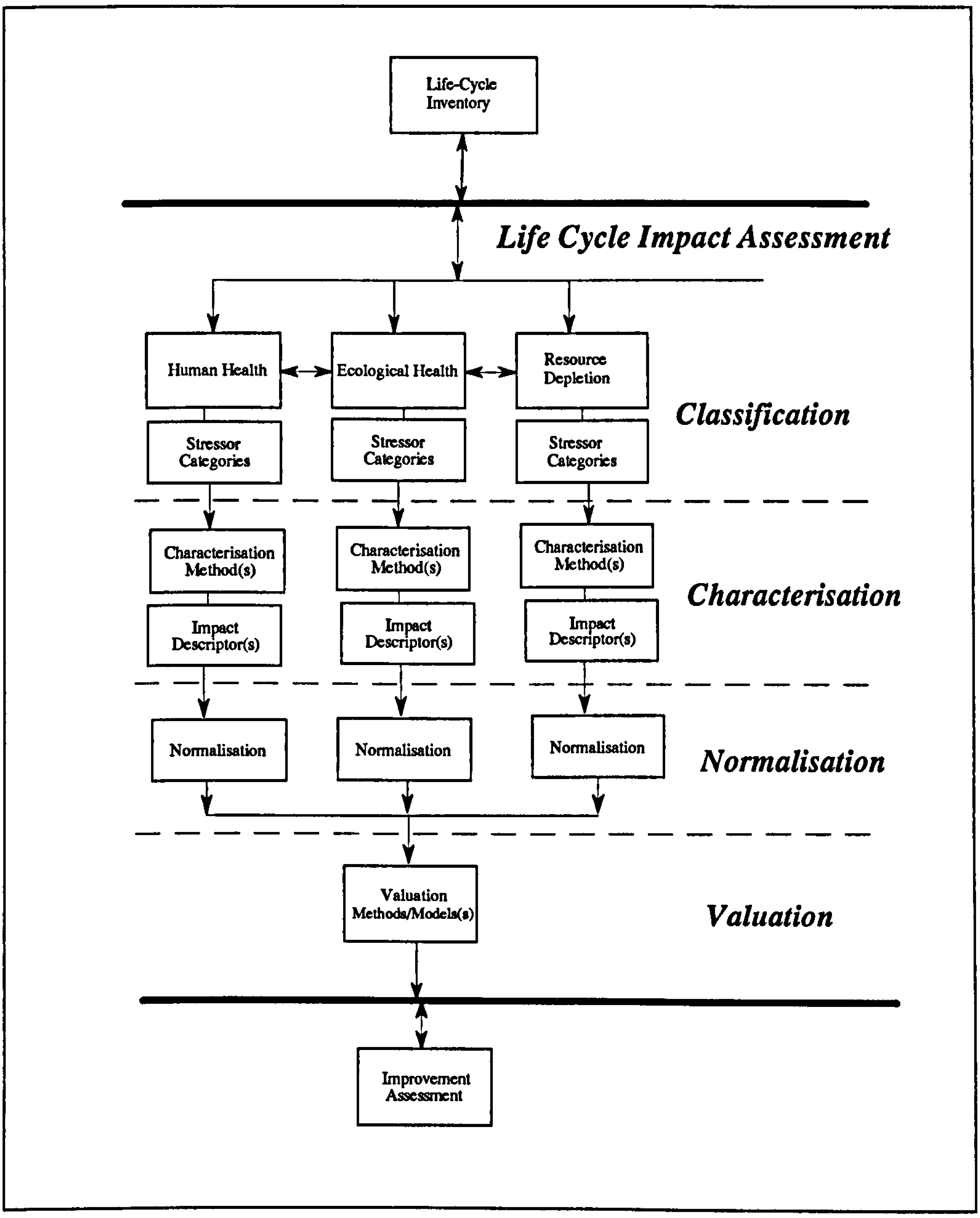

Figure 2.5 Framework for impact assessment

Five characterisation methods were proposed following the outcome of discussions held at the 1992 SETAC workshop in Florida [SETAC 94b]:

(i) **Loading assessment.** This is a simple accounting of the loadings to the environment and consumption from the environment, expressing them as mass per use equivalent of the product, process or activity. Examples of such methods are: Less is better (group data from inventory table without further analysis), Checklist approach, Relative magnitude approach, Green indicator approach, Impact analysis matrix approach and Judgement probability encoding approach [SETAC 94b, Allen 94].

(ii) **Toxicity equivalency assessment** aggregates emissions to their potential effects without any exposure analysis. The mass loadings from the inventory (expressed as mass per unit product) is normally divided by a toxicity standard such as a reference dose. Examples of such methods include: Critical volume approach. Ratio of (Emitted amount/ No-effect-concentration), Environmental priorities strategies (EPS) approach, Tellus hazard ranking (Control costs) approach, Human exposure dose/ rodent potency dose (HERP) index, Degree of hazard ranking approach, Resource consumption ration approach, Time-metric resource depletion approach and Resource integrity index [SETAC 94b, Allen 94].

(iii) **Toxicity equivalency assessment with modifying factors.** This is identical to (ii) except that it aggregates emissions separately to their inherent toxicity (or potential effect), persistency and bioaccumulating behaviour from the human standpoint. Some of the available methods are: Toxicity, persistence and bioaccumulation profile approach and Degree of hazard evaluation approach [SETAC 94b, Allen 94].

(iv) **Generic exposure/ effects assessment.** The previous three do not deal with exposure. However, this assessment aggregates emissions based on a generic analysis of the exposure and also the effects due to a particular emission, sometimes taking into account generic background concentrations. Generic assumptions about human exposure can be made, and in combination with toxicity data, human health impacts could be predicted. Examples are the characterisation of ozone-depleting emissions according to ozone depletion potentials, the characterisation of greenhouse emissions according to global warming potentials (GWP). These methods result in one general effect score per problem type [SETAC 94b, Allen 94].

(v) **Site specific exposure/ effects assessment** aggregates emissions based on a site specific analysis of the exposure and also the effects due to a particular emission, taking into account site specific background concentrations. Classical risk assessment methods and models are employed here and the results are expressed as individual or population probabilities of occurrence [SETAC 94b, Allen 94].

The last step of characterisation is the normalisation of effect scores obtained from the previous stage. Sometimes, this may be omitted or may be performed as a separate subcomponent or as part of either the characterisation or the valuation. The object is to allow the user a reference value for comparison. Several normalisation methods have been developed [Lindfors 95], however normalisation data are only valid if the same method is used in the characterisation.

Valuation is the final stage of the impact assessment. Based on the environmental profiles of the products studied, valuation takes into account the reliability and validity of the results by performing sensitivity analyses. The valuation will involve, ideological and ethical values. These can be performed using either qualitative or quantitative methods.

Qualitative valuation methods can often be seen as methods for structuring information provided by the LCA. They are often designed to help draw conclusions from a study. For example, in the qualitative multicriteron analysis ("apples and oranges" method) effect scores are weighted against each other in a non-formalised way [Allen 94]. For each separate case study, the weighting is performed by an individual expert or by a panel of experts. This method is followed by several countries in their ecolabelling [Guinee 93]. Other examples of qualitative methods are those developed by Allenby [Graedel 95b] and Schmitz et al [Schimtz 94]. The former requires pictorial ranking of the impact of a set of predefined "sources" (such as local air impacts and waste impacts) to a set of predefined "critical properties" (such as transportation and initial production), whilst the latter requires a verbal ranking (in order of importance) of five criteria from different impact categories.

The quantitative valuation methods may be divided into three main categories: (i) Panel methods (ii) Monetarisation methods (iii) Distance-to-target methods. In the first category, the methodology employed is similar to qualitative approaches, except that people are asked to express their opinions in a quantitative way. Examples conducted using this approach involved two different Dutch studies [McKinskey 91, Kortman 94] and a British study [Wilson 94] using some form of weighting factors such as awarding points and ranking using questionnaires.

Monetarisation methods are based on either "willingness to pay" and methods that are not. The former method may be divided into 3 approaches: Individual's revealed preference (assuming that people reveal their preferences in the market prices such as in the Travel cost method [Finnveden 96] or Hedonic pricing methods (which assess the environmental influence on the pricing of commodity [Finnveden 96]), Individual's expressed preferences (based on non-user values not derived from revealed preferences such as those used in the Contingent valuation method for valuing threats and damages) and Society's willingness to pay (to be derived from political and governmental decisions as employed in the Tellus system where data on emission taxes and marginal costs for reducing emissions to a target limit are used). Methods not based on "willingness to pay" are often concerned with the cost estimation of doing something, however it is not clear who is willing to pay the cost of the action. An example may be the marginal cost for removing the pollutant to an emission limit (DESC method) or remidiation of a damage.

Distance to target methods of valuation are based on the relation of the valuation weighting factors to a set target. The methods are usually defined by a precise equation, the simplest being $V = 1/T$ where V is the valuation factor and T the target. This equation was used by Schaltegger et al. [Schaltegger 91] where the target level was different types of quality standards expressed as amount per mole of media (air and water). The valuation used data from the inventory analysis. The differences between different distance-to-target methods are reflected in the shape of the equation, choice of targets and the type of data used (i.e. from inventory or characterisation).

2.3.2.4 Improvement analysis

The purpose of the improvement analysis is to systematically evaluate the needs and opportunities to reduce the environmental burden associated with energy and raw material use and waste emissions throughout the life cycle of a product, process or activity. Improvement opportunities may be based on the results of inventory analysis, impact assessment, or some combination of the two.

Improvement analysis is the least developed component of LCA. To date, improvement of products has been undertaken by designers on a trial-and-error basis using empirical knowledge on environmental properties of materials and processes. In the context of LCA improvement analysis has not yet been formally discussed in a public forum. Thus, for the purposes of LCA, improvement assessment is both conceptually and methodologically deficient.

2.3.3 Limitations and areas that require further work

Though LCA has been in development over two decades, the current status of LCA appears to have firm establishment only in the inventory stage. A survey of LCA software tools such as those of Boustead, Franklin Associates, Chem systems, PRe' consulting, and Battelle indicate that they primarily assist the inventory analysis step in an LCA with limited impact assessment functions [Menke 96]. Moreover, available quantitative data often appear to be in an aggregated/ composite form, the lack of transparency often affecting the credibility of life cycle inventories and the methods performing them. Although there are initiatives to publish non-aggregated baseline data for public access such as the study on packaging materials by EMPA St. Gall (Swiss) [Koller 94], such initiatives remain rare and expensive to perform. Schaltegger

[Schaltegger 96a] argues that as the cost of collection for LCA data increases, the quality of the data declines substantially with distance from the firm (see figure 2.6). The cost curve in the post production process tended to be even steeper in practise as such data requires collection from an even wider background.

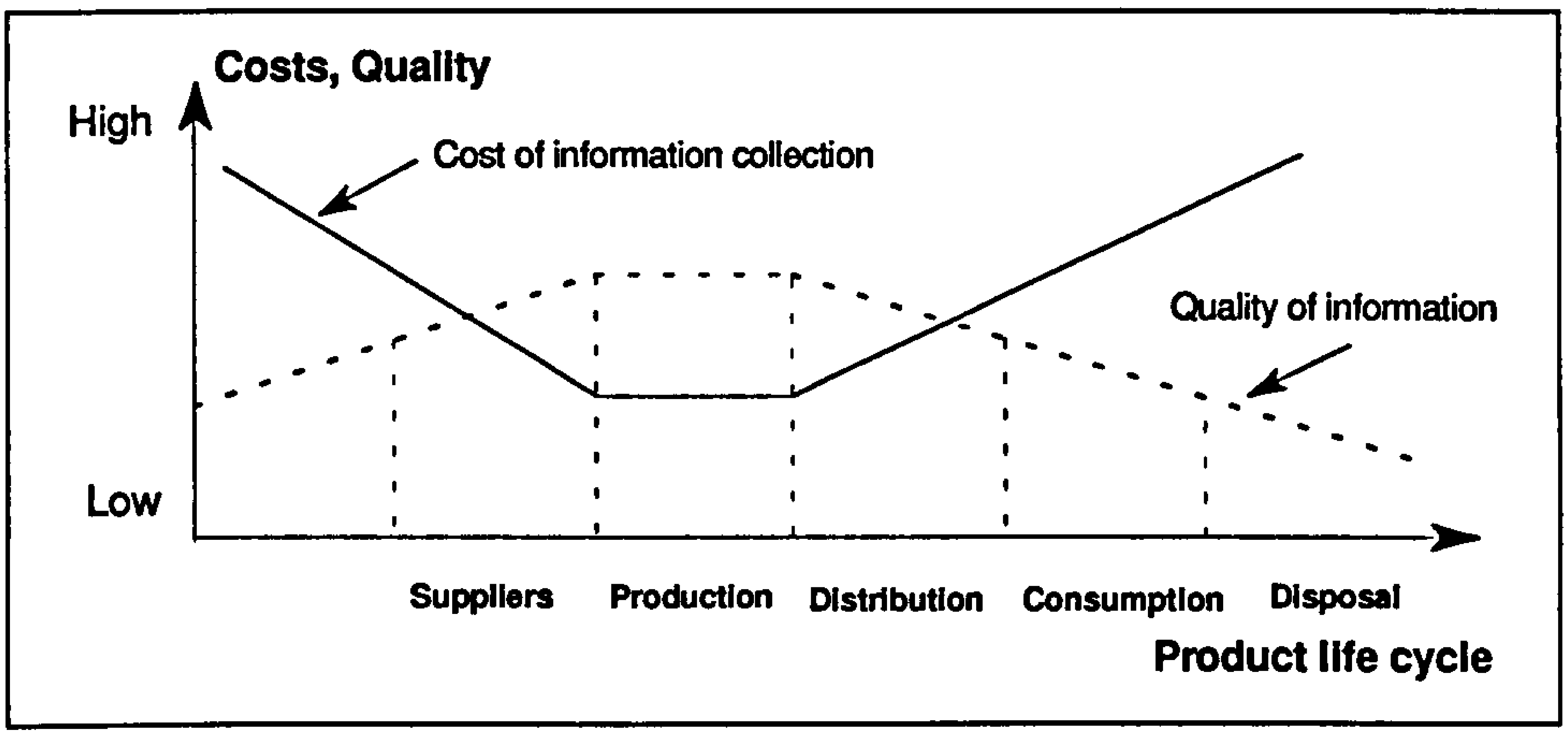

Figure 2.6 Costs of information collection versus quality obtained in a product life cycle [Schaltegger 96a]

Background inventory data (databases for downstream processes such as sewage plants) often represent an industry average and tended to mask the highs and lows of both good and bad manufacturers. The potential of such aggregated errors in an LCA could be large and may be too distorted or aggregated to provide any useful information in management accounting [Schaltegger 96a]. From an economic viewpoint, the results from an LCA could only provide credible information to stakeholders when they have been audited by credible third parties to formalised standards. Currently, such practise exists only for environmental management of sites and firms (EMAS and ISO 14001).

When comparisons are made using different methods, they usually bring out very different priorities of the environmental burdens. In the case study of the environmental impact of paper cups versus the polystyrene foam cups for single applications [Hocking 91] it is commonly assumed that a paper cup is more environmentally friendly than the polystyrene one. However, the research shows that the paper product requires more raw material; the inorganic chemicals needed in the paper making process, together with the large relative amount of water effluent, provide substantial off-site impacts compared with the only significant emission associated with the polystyrene cup: the pentane used as a blowing agent. The polystyrene cup is easier to recycle and approximately as easy to incinerate. Landfill degradation has been thought to favour the paper cup, but recent studies show that even "biodegradable" materials remain undegraded in anaerobic landfills over very long periods, rendering the advantage relatively unimportant.

There are also a number of developments within LCA that could be seen as impediment to its effective practice. A great deal of research performed in the past few years has led to a flourishing of conceptual methodologies particularly in impact assessment. Although this has helped to structure the general approach to the problem issue, it has also nevertheless complicated the application of LCA due to the many inconsistencies in methodologies and variations among practitioners. This is also likely to impede comparisons between products over a time horizon. The cost of conducting a full LCA is high and often not viable technically (due to data gaps) as well as financially. This has led to the development of abridged versions such as one employed at AT&T [Graedel 95c] where "target plots" are used to focus on problem areas for potential improvement. Another limitation of LCA is that it often appears to be like taking a "one time snapshot" of a complex phenomena. Current ecological calculations are often based on single samples that are rarely resampled in subsequent periods [Schaltegger 96a], it is also difficult, if not impossible for product consumers to verify the analysis or the accuracy of the data. With the lack of methodologies to update and reuse the results it should not be used as a justification tool for a product (i.e. that products should not face disapproval on the basis of a negative life cycle assessment). LCAs are not fixed quantities but are dependent on technical developments and therefore require constant re-evaluation [Zürn 94].

Over the last two decades, most LCA studies have been dominated by packaging projects such as beverage containers, food containers, fast-food packaging, and shipping containers. Recently, an increasing number of other compound products have been evaluated, these are mostly financed by the product suppliers: diapers, household products and textiles [Wenzel 94]. As LCA is beginning to expand its boundaries into other applications, it will have to effectively address the less established areas of development, that of standardising impact issues and further developing improvement assessment.

There is an overall need for close collaboration of industrial ecologists with environmental scientists and across national boundaries to avoid widely varying ranking standards. At the same time, there must be harmonisation across cultures as the assessments will reflect the value system of the community performing the prioritisation. It is envisaged that the impending ISO 14040 standards for LCA will embrace the above goals. It is also proposed that material suppliers be encouraged to make inventory analyses of emissions and natural resources to a central managing body i.e. to supply data with an average value for one material in a similar practise to APME (Association of plastics manufacturers in Europe) [Nygren 94]. This will facilitate calculations of impact indices such as the No-Effect-Concentration (which has been developed to protect the majority of species in the ecosystem by statistical projection of toxicity over a limited range of data). It is found that the more data that is available for calculating NEC, the less restrictive (higher) the NEC value will be - this could be an added incentive for the "polluter" to provide more data [Wenzel 93]. On the whole, there is a need for more data in particular background inventory and site specific data [Schaltegger 96a]. The former is likely to lead to better software databases and more robust LCA procedures whilst the latter will lead to better product-specific information and may also encourage regulatory incentives for site-specific ecological accounting similar to EMAS and ISO 14001.

A valuation of environmental profiles without an assessment of the reliability and the validity of the results, is of little value. To date, a systematic treatment to test the credibility of the results obtained is lacking. Assumptions and choices underlying the methodology and the particular case study will inevitably influence the findings of the study. Though US-EPA guidelines recommend a peer review for independent verification of results [EPA 93d], a systematic methodology should be developed for this purpose.

For the improvement of products, knowledge of the dynamic behaviour of the environmental profile in terms of process modifications is very important. The improvement analysis of an LCA can structure this process. To date, improvement assessment is both conceptually and methodologically deficient although initial attempts have been made to work out possible approaches by Heijungs [Heijungs 94] using dominance and marginal analysis methods. Other techniques may include both quantitative and qualitative measures of improvements.

Given the present shortfalls of LCA methodologies, Graedel [Graedel 94] sees two actions: (i) to continue with LCA since large potential benefits can still be achieved even with simple approaches (ii) work towards a more uniform and standardised approach.

2.3.4 Life cycle assessment application examples in the electronics industry

A number of areas of potential environmental improvement have been identified within the electronics industry, however there exists no current single set of consolidated environmental data about the electronics industry [MCC 96c]. One of the reasons being LCA on electronic components is still a relatively new and complex process. As more materials and chemicals data become available and the methodologies for complex LCAs develops, it will become easier to identify significant impacts that are associated with the manufacture, use and disposal of electronic components. There are nevertheless prominent environmental improvements being made, these include: replacement of CFCs in circuit board manufacture, reducing the energy requirements of equipment both on and off-line, redesigning of packaging materials to include recycled materials and reducing overall packaging and pollution prevention measures in the production cycle.

The Energy Star program, launched in 1992 by the US-EPA has seen more than 2000 models of computers, monitors, and printers from some 400 manufacturers in the US meeting the Energy Star criteria. "Sleep" modes, which reduce the energy consumption of products when they are not in use, are now common features to Energy Star computers [Perry 95].

In March 1993, the Microelectronics and Computer Technology Corporation (MCC) published an exhaustive life cycle study of a computer workstation with the observation that energy was consumed most in the use stage of the product followed by the PCB/ assembly process [MCC 93]. The study has contributed towards better understanding of various materials issues including the minimisation of recycling costs such as energy, management, transportation as well as waste disposal. In their 1996 road map the MCC addresses a wide ranging set of critical issues relating to strategic environmental management through product design, assembly and distribution [MCC 96c].

An independent LCA study of a computer workstation was conducted at ABB Corporate Research in Sweden using the Environmental Priority strategy (EPS) system developed by the Swedish Environmental research institute (IVL). The Order for top 3 environmental impacts from highest to lowest are: (i) energy consumed during use (assuming a normal working life of 10 years), (ii) depletion of cadmium as a natural resource (which may be reduced by recycling), (iii) air freight of manufactured goods to customers in USA/ Far East. Waste deposit is found to have low impact on the environment due to low leakage - the only impact lies in landfill. It is recommended that ashes be cemented/ glassified, all metals to be recycled and plastics be incinerated for energy recovery [Nygren 94].

At IBM Sweden, an LCA was performed to compare the alternative materials for the paper feeder of the IBM printer 4234. The EPS system was used to asses the ELUs for different materials. It was found that the use of pressure die-cast aluminium (containing 90% recycled material) used only a fraction of the energy consumption of primary aluminium. Furthermore, toxic Cr (VI) and Zn are eliminated, less energy is also required to machine and assemble the shafts. Since both shafts and stands can be recycled - the pressure die-cast aluminium stood out as a better alternative to using primary aluminium in closing the materials loop [Lundgren 94].

Ecobalance Incorporated (USA) conducted a seven month LCA study for an electrical switch. The claim made by one company is that their switch was cadmium free while identical switches made by others were not. The claim was based on the contact component alone. This claim was later refuted through the use of an LCA in considering the entire life cycle of the switch. It was found that the competitor's Cd/ Ni contact was not "worse" than the nickel one. The release of cadmium from the contact is not significant as it concerns with only a small part of the overall cadmium released during the entire life cycle. Actually, most of the cadmium was released from another stage of the life cycle (metal coating) - a fact that was not mentioned or considered in the advertised claim of eco-friendliness [Besnainou 94].

A Pre-LCA tool is being implemented at Digital Equipment to help designers interpret and draw out design implications by observing: energy and waste minimisation, safe and efficient disposal, reduce/ reuse/ recycle options. The Analytical Hierarchy Process (AHP) method is used in the final output analysis to yield a single environmental figure of merit. The Pre-LCA is used as a comparative tool to evaluate options of similar functions and was demonstrated by a case study of alternative materials for video display shipping packaging [Tolle 94].

An LCA study performed at Nortel (UK) for aluminium vs. plastic versions of a 16" subrack panel for SDH telecommunications equipment indicated large gaps were found in the information available in both the Boustead (only 4 out of 13 items) and PEMS (only 3 out of 13 items) databases, especially on engineering plastics and plating chemicals in the metallisation steps. An experimental Dutch scoring system was then applied for the impact assessment. The results indicated the aluminium subrack is a better choice in reducing resource depletion, nutrification potential, photo chemical oxidant formation whilst the plastic subrack is better for the reduction of global warming potential and acidification. Ozone depletion factor was zero for both cases [Snowdon 94].

An enhanced Boustead database was used for the life cycle assessment of the cover for IBM PS/2 model 95. The study was undertaken by Scientific Certification Systems (SCS) for IBM. The enhanced database contains an "inventory evaluation" conversion engine in which the raw data outputs are aggregated under approximately 20 impact descriptors. Results indicated that: (i) reductions in environmental burdens associated with electro-galvanising are significant compared to aluminising and galvannealing (ii) Powder-based paints are better than water-based paint since the former offers more complete utilisation of materials [Brinkley 94].

LCA studies were conducted by Ecobilian in France to investigate the different end of life solutions for the disposal of cathode ray tubes using both closed loop and open loop recycling strategies as well as landfilling options. The studies indicated that less lead is emitted in the first and third case whilst more energy is saved in the second. On the whole, closed loop recycling is preferred to landfilling [Epelly 95].

A LCA assessment of a telecommunications semiconductor laser was conducted using energy data from Boustead and PEMS [Donalson 1996]. The various life stages examined included manufacture, packaging, transport to customer and disposal. It was found that the use phase of the laser demanded most energy and that small efficiency changes may over a lifetime of 15 years yield energy savings and lead to reductions in environmental impacts.

At the Swedish Environmental Research Institute (IVL), LCAs were carried out on both tin-lead and silver-epoxy solder conductive adhesive as potential substitutions for lead [Segerberg 96]. The results indicated that the environmental effects of silver, tin and lead wastes are very uncertain and are highly dependent upon loading conditions of the three during production. Since the three materials are loaded simultaneously in most cases, LCA findings were inconclusive.

At Nokia research centre (Finland), an LCA study for telecommunication cables was conducted by considering all manufacturing processes from raw material acquisition to the final disposal of the product. SimaPro3 analyst software was used in the study and results indicate that the most significant environmental improvements can be found in changing the sheathing material and the way of disposing the used cable [Terho 96].

An LCA of an inkjet print cartridge was performed by HP, the results indicated that printers with double-sided printing allow for significant environmental savings. Changes in the formulation of the ink are required to perform well on recycled and alternative fibre papers. The incorporation of power saving features in the printer is also likely to save nearly half of the electricity impacts. In addition, the change in packaging also helped with the distribution energy of the product across the life cycle costs [Pollock 96].

The LCA study of a photocopier was performed by Xerox using a comparison of three data types: Xerox data, DEAM software database and hypothetical data. Results identified carbon dioxide as the largest emitted compound while water consumption is the dominant resource used. The study also concluded that LCA is perhaps currently not a good tool for comparing competing office products but is useful for internal decision making [Calkins 96].

2.3.5 Conclusions

This review is by no means complete or exhaustive both because of the rate of change in LCA development and also due to the lack of access to translations of German, Dutch and Japanese texts. However, the following conclusions may be drawn.

Life cycle assessment is not a linear or stepwise process. Rather, information from any of the three components can complement information from the other two. Environmental benefits can be realised from each component in the process. The inventory analysis alone can be used to identify opportunities for reducing emissions, energy consumption and material used. The impact analysis addresses ecological and human health consequences and resource depletion, as well as other effects such as habitat alteration that cannot be analysed in the inventory. Data definition and collection to support impact analysis may occur as part of inventory preparation. Improvement analysis helps ensure that any potential reduction strategies are optimised and that improvement programs do not produce additional, unanticipated adverse impacts to human health and the environment.

The areas of LCA that require significant development include standardisation of impact assessment methodologies and the further development of improvement assessment. This is in part due to the lack of agreement on environmental impact issues which calls for socio-political consensus across national boundaries and also in part due to the requirement for more robust and efficient methodologies. However, the use of LCA in its present state is justified on grounds that large potential benefits are continually being achieved even with simple approaches. This is evident from the application case studies in the electronics industry.

2.4 Design for 'X' - design issues in support of sustainable product development

2.4.0 Introduction

This section will review design issues related to sustainable product development. Following the broader discussion in section 2.0.1, sustainable development may be seen as a dynamic state that harmonises economic activities with ecological processes [Keoleian 96]. In the past two decades, a series of generic methodologies addressing a spectrum of design issues ranging from assembly to end of life have emerged. The application of such methodologies in the past appears solely to address financial goals, recent evolution of design strategies, especially those which embrace the life cycle concept, has tended to be driven by a mixture of ecological, legislative, cultural as well as economic concerns. These methodologies use either generic descriptive guideline matrices, quantitative scoring procedures or are based upon a mixture of both and can be fairly product specific. This section will examine a few pertinent Design for 'X' methodologies associated with sustainable product development, where 'X' is a desirable product characteristic such as manufacturability, testability, reliability or safety. Most DFX tools apply to only selected life cycle stages such as disassembly and recycling, which in practise can be considered as an integrative combination of different DFX tools. The particular DFX approaches reviewed here include:

- Design for environment/ Life cycle design
- Design for disassembly and recycling
- Design for reuse and remanufacture
- Design for service

2.4.1 Design for environment/ Life cycle design

Design for environment (DFE) and Life cycle design (LCD) are concerned with applying environmental criteria aimed at the prevention of waste and emissions and the minimisation of their environmental impact, during the material life cycle of a product [van Weenen 95]. By incorporating DFE as part of the existing DFX design system, two possible advantages may be realised [Allenby 94]. Firstly, linking DFE into existing processes will reduce the culture shock of suddenly fully integrating environmental considerations into product and process design, making the entire package more acceptable and easier to implement. Secondly, DFX imposes a discipline on DFE development to fit into existing design procedures thus making it more practical in a real operating environment. LCD and DFE in practise are difficult to distinguish from each other, they are usually considered as different names for the same approach; however the genesis of DFE (as an evolution from DFX approach) is rather different from that of Life cycle design.

Product life extension appears to be at the top of the hierarchy of LCD strategies. Van Weenen observes that the current product oriented approach has paid too much attention to the end-of-life product concerns such as waste problems, take back, reuse and recycling [van Weenen 95]. What is needed is a broader approach that considers "prevention" as a starting point and aims to reduce environmental impacts across the whole product life cycle. However the creation, synthesis and evaluation of a design is shaped by a number of external forces such as market demand, government regulations and polices, infrastructure, state of the economy and environment, scientific understanding of the risks, public perception of these risks as well as a number of internal forces. Internal forces are mainly attributed to the appropriate selection of corporate policies, goals, performance measures and resources to support Life cycle design projects. Management in particular plays a vital role [Keoleian 96]. Life cycle design aims to achieve a balance of these environmental, performance, cost, cultural and legal requirements.

Currently, many DFX tools have been proposed and discussed to facilitate the development of DFE and LCD. However most DFX tools apply to only specific life cycle stages, the evaluation of design decisions appears to be the weak point of DFX approaches. Most rely on either qualitative check lists or intuitive point scoring systems which may not be sufficient to solve trade-off relations [Hattori 95]. More recently, Life cycle assessments (LCA) have been incorporated into DFE. The LCA methodology generates data on environmental impacts which represent an important component of a DFE approach, however LCA and related approaches are evaluation tools and do not provide a mapping of environmental burdens and constraints into product and process design, as DFE does. DFE is comprehensive and incorporates familiar concepts like "pollution prevention" and "toxic use reduction" with other necessary dimensions such as "Design for disassembly and recycling", "Design for reuse and remanufacture" and "Design for service". These will be dealt with in more detail later in the chapter.

When implementing a DFE program, Allenby [Allenby 94] distinguishes between two categories: (i) global comprehensive projects that extend across all design functions and (ii) specific evaluations of products, processes and inputs. The former, will require review of all internal specification documents to determine potentially harmful processes and components such as chlorinated solvents or lead solder used with in conjunction with epoxy systems. Generic contract clauses may be used to change supplier behaviour like the use of non-CFC packaging. Unnecessary process steps could be identified and eliminated to reduce environmental impacts across many operations. An example could be cutting down the emissions of CFCs and chlorinated solvents by reducing the number of cleaning steps. In the latter category, which evaluates specific products, processes and inputs, a framework using three basic steps may be applied. These are: (a) scoping to determine the depth of analysis, (b) data gathering in at least four areas which include environmental, manufacturing, social/ political, toxicity/ exposure primary elements, and (c) data translation into easily digestible formats such as generic design procedures and checklists.

The practical aspects of implementing DFE are compared in a case study of four companies (Xerox, AT&T, IBM and HP) by Shelton [Shelton 95]. One of the crucial lessons learnt from successful DFE users is that critical mass is a red herring - DFE programs should start small and expand incrementally. A large centralised DFE organisation may very well induce disputes between central and operating units in the product and development process. This type of tension occurred at Xerox when the operating division questioned the value of corporate-mandated DFE. Only after it was internalised to the division, did the product take back programme begin to take hold and grow. The best way to avoid these problems is to start small and use a specific operation and product line as a pilot project. A similar approach was used by HP when DFE was first introduced in the company. However, Shelton warns that DFE expansion will be uneven as it expanded to other parts of the organisation. In particular, companies should expect resistance and uneven adoption among divisions as some managers will remain inherently sceptical about it - this is the case in most, if not all, of the companies surveyed.

While DFE methods are being an increasing developed as a competitive tool for products [Weston 96, Lucacher 96, Jonhson 95] there appears to be no consensus on a proven set of DFE practises. This is evident in the diversity of titles for corporate DFE schemes. Most DFE tools are developed in-house and address only specific life cycle stages and are normally guidelines and checklists instead of detailed analytical tools [Lenox 96]. This again points to deficiencies in existing tools. One of the biggest problems faced by designers in DFE is the lack of reliable data on materials, parts, and components needed for trade off decisions. According to a survey of current DFE practises by Mizuki et al. [Mizuki 96], the ideal DFE tool should have the *intelligence* to allow the designer to make informed choices at every stage of design and be supported by a common set of metrics and common vocabulary for meaningful comparisons and measurement of progress and other means of communicating environmental trade-offs. In addition Lenox et al. argue that the adoption of DFE is to be brought about by the management of innovation and organisational change - better management will only arise from a sound understanding of the organisational aspects surrounding DFE [Lenox 96].

2.4.2 Design for disassembly and recycling

Current work in disassembly addresses two important issues: (i) that of relieving the urgent need to deal with present end of life products, and (ii) provide a foundation for future development of disassembly methodologies.

Pioneering work in this area arose largely from the need to generate robotic assembly and disassembly (as the reverse of assembly) sequences using geometric/ relational and precedence relationships. In a geometric/ relational model, the contacts are given by geometric relations for part mating and occur between pairs of compatible surfaces, such as planar, cylindrical and threaded surfaces. The work of Subramani and Dewhurst [Subramani 91a], Homen de Mello and Sanderson [Homen de Mello 86] are examples that employ this algorithmic method of part mating. In the case of a precedence model, consideration is given in the absence of a part that gives more freedom of movement to another part, the former will have *precedence* over the latter. The precedence relation is local to the parts concerned and does not appear to take into account of other precedence information in the assembly. This method was used as a basis of the work by Bourjault [Bourjault 84], Defazio and Whitney [Fazio 87] and Yokota and Brough [Yokota 92].

The above methodologies are based on ideal part mating conditions and do not appear to represent the complexity of real situations. The encapsulation of various cost metrics, probability and time estimates factors are common to later methodologies.

Examples of work by Dewhurst, Zussman et al., Dowie, Hitachi and Suga et al. are briefly reviewed here. Dewhurst [Dewhurst 93] employed the structure diagram produced from a "Design for Assembly" analysis to estimate the disassembly time and the subsequent estimated reassembly time of a product. The service efficiency index for a product was developed which took into account various costs items such as service replacement parts and labour, disassembly and resassembly timings. The disassembly time that will achieve the optimal recycling efficiency has also been derived.

The work by Zussman et al. [Zussman 94, Zussman 95] has seen the development of a disassembly oriented assessment methodology that works out feasible routes for disassembling a product using AND/OR graphs [Homen de Mello 86]. For every node in the graph, choices must be made either to continue disassembly or to apply other end of life options to the component (such as recycling or dumping). The optimal path is reached upon satisfying the condition of maximum profit of product recovery.

Dowie [Dowie 95b] has also proposed a disassembly planning process that could be applied to various stages in the product life cycle to enable disassembly and recycling of products to be planned and optimised effectively. A precedence relational model was used to determine the disassembly sequence and the depth of disassembly is bounded by the criteria of notional profit. The work has also led to the development of a set of synthetic timings over a range of disassembly operation such as screw removal, opening of snap fits, plastic deformation and desoldering. Various disassembly and recycling indices have also been derived to help rate the product in terms of criteria such as compatibility of materials, number of fasteners and product recyclability.

The company goal at Hitachi to reduce disassembly time of products manufactured in fiscal 1995 to 50% of disassembly time of products manufactured in fiscal 1992 has resulted in the development of the Disassemblability Quantitative Evaluation method [Kamei 95] that evaluates the difficulty level associated with the disassembly of new products. Two indices are proposed, one being the ease of disassembly score (on a scale of 100 points) and the other a disassembly cost index under normal working conditions and both can be estimated using drawings alone. This tool is employed to compare and highlight potential design changes in both Hitachi designs and that of other companies in the bid to identify potential areas for improvement.

Recent work by Suga et al. [Suga 96] has moved away from conventional geometric and precedence approaches to one which is based on energy and entropy for disassembly. The total energy for disassembly is calculated by summing up the contributions of each fastening point and the debonding energy over the joining areas. The method was investigated by dismantling six personal computers. The net disassembly time is correlated to the disassembly energy, while the difference between the actual disassembly time and the net disassembly time are accounted for by the disassembly entropies.

One of the major obstacles encountered in the recovering products for disassembly and recycling is the lack of specific information regarding the product and estimating the remaining life and reliability of its component parts. The "green port" project under the European "CARE VISION 2000" initiative was being set up to address this problem [Scheidt 94, Scheidt 96]. The "green ports" are small electronic identification tags that are attached to products to provide life history data such as hours of operation, materials used, list of additives, name of manufacturer and date of manufacture. The green ports have the potential to map the component and materials characteristics to each individual product to provide important information upon disassembly.

There has also been increasing interest in the disassembly of electronic products, in particular, PCB disassembly. This is because printed circuit boards contribute towards a significant disposal problem as a result of the presence of complex and potentially toxic substances. As manufacturing printed circuit boards out of a single environmentally friendly material is not possible at present, design for disassembly and disposal may appear to be the only green alternatives. In the case of reusing surface mount components, solder is first removed by heating selected board areas, the component IC chips are then removed. Two basic methods employed are "look and pick" and "evacuate and sort" [Feldmann 94]. The former requires exact knowledge of the location and normally results in less damage while the latter requires the whole board to be heated for desoldering and components then being removed simultaneously and sorted. The "evacuate and sort" method although increases the risk of damage, it is relatively fast. Feldmann et al. [Feldmann 94] identified that irrespective of the methods chosen, the risks for functional damage to the integrated circuit chips are a combination of heat to loosen the solder and the amount of force required to remove the components. Other factors include adhesion of the glue that holds the chip in place during assembly, pin size and the friction created between the pin and board material.

Another approach to extracting chips from boards is suggested by Heeselbach et al. [Hesselbach 94]. which involves first identifying the components using optical methods (such as laser scanning, line scanner and coded light methods) and than cutting the required board area using a linear slicing movement to remove the chips. Lee et al. [Lee 96] proposed using either a destructive approach or non-destructive approach to disassemble multi-component boards. Surfaces between components are first examined for separation without destruction. A Gaussian hemisphere is used to determine if the component can be removed freely in 3D space without obstruction. Only planar cuts are used if destruction is necessary. At that point non-destructive chip removal begins. Moyer et al. [Moyer 97]notes that chip disassembly can be a very tedious and costly manual task, but to date mechanical alternatives are also costly due to the requirement of sophisticated recognition systems. The cost of disassembly alone appears to be a factor that discourages manufacturers from developing more environmentally conscious practices.

However, Wittenburg [Wittenburg 92] pointed out that if products are to be made for economical disassembly in 30 years or so ahead, it will require understanding of disassembling and recycling techniques now being contemplated and the vision of others not yet conceived. Recycling/ disassembly efforts in the electronics industry have seen significant advancement in the past few years. A growing number of multinational companies such as Phillips, IBM, HP, Digital, Kodak and Hitachi have environmental programs that incorporate recycling initiatives using either in house facilities or sub-contracting. The current British Telecom-Frazier partnership in telephone recycling is a typical company-recycler partnership example which has seen 2.5 million used phones recovered for reuse, remanufacture or recycling in 1995/96 [Deloitte 96].

To facilitate disassembly of parts and materials, MCC [MCC 96d] identified the following issues to be addressed:

- Increasing the recyclability of all components
- Easing the disassembly and identification of component parts
- Protect OEM sensitive/ confidential information
- Encourage OEM to support creative applications for recycled products
- Develop global and cross-industrial recommendations and initiatives, including parts and materials reuse.

With heightened awareness in environmental conscious manufacturing, many companies are already practising this environmental ethic, those that do not will probably be forced to act upon public demand and legislative orders [Magee 97]. Research into new and improved methods will continue to make disassembly and recycling activities a more sustainable and profitable operation.

2.4.3 Design for reuse and remanufacture

Environmental impacts can be significantly reduced by reusing products in which the added value of the product is retained and is reused for the same purpose as during the original life cycle [Navin-Chandra 93]. Additional savings in resources can be obtained by integrating reuse with remanufacturing which is in itself is a process of bringing products up to quality standards that are as rigorous as those of new products [de Ron 95].

Current applications of reuse appears mainly restricted to household products such as refillable soft drink and detergent bottles and rechargeable batteries or in secondary purposes such as the reuse of automotive tyres as mooring cushions in harbours. On the industrial level there has been increasing promotion in reusing packaging materials such as corrugated plastic, vacuum formed trays, knockdown bulk bins, steel containers, internal protective packaging and plastic pallets. Although the switch to reusable packaging appears to be a significant investment, the financial costs may be off set by a faster cycle time when used and refilled, especially for frequent shipment of the product to the same location [Vickery 96].

Reusing of parts is often combined with remanufacturing processes in engineering systems. However, remanufacturing is normally performed on products that have a high replacement cost or have valuable components which can be cost-effectively reused or reconditioned. It plays a significant role in diverse industries such as aerospace, automotive, construction equipment and medical equipment [Levine 93]. In the US, remanufactuirng is most predominant in the Department of Defence and most visible in the automotive industry [Amezquita 95]. More often than not, the actual remanfacturing is often undertaken by third party vendors as Original Equipment Manufacturers (OEMs) do not consider it their core business. However, an increasing number of OEMs are directly involved in remanufacturing their own components such as Xerox [Berko-Boateng 93] and Siemens Nixdorf [Siemens 94]. There are two possible advantages can be achieved through this arrangement: (i) by offering a remanufactured warranty equivalent to the original warranty and (ii) by exploiting their product design to enable products to be remanufactured more easily. These combined factors would enable an OEM to gain an overall competitive advantage by both presenting a green profile and boosting profitability of remanufacturing. In the Xerox example, the company has developed a reclamation scheme where machines may be returned at the end of their service or lease life. They are then remanufactured to their original quality and returned to service. Assembly of new and old copying machines are done on identical assembly lines, this reflects the modularity and standardisation of parts in the overall design which permits remanufacturing of older machines without having to make out of date replacement parts.

The electronics industry is beginning to think more about reuse and remanufacture than in the past [Davis 96g]. Whenever there is a market demand for a product which can be priced lower than equivalent new products and also be cost effectively remanufactured, the potential for remanufacturing exists. The remanufacturing of printer toner cartridges and "disposable" cameras are typical profitable enterprises. MCC outlined the major areas needed to be addressed for reuse in electronic products as follows:

- Customer-vendor co-operation is needed in providing technical support for reused components as many parts contained in electronic equipment are purchased by equipment manufacturers from parts vendors.
- Robustness, reparability, easy access should be designed into parts.
- Develop test procedures to ensure reliability and performance.
- Technologies for tracking parts life and the number of life turnovers.
- More environmentally conscious cleaning technologies, as current cleaning technologies still rely heavily on halogenated cleaning solvents.

Those outlines for the use of remanufactured parts in products include:

- Incorporation for reused parts into government and industry procurement practices.
- Parts and equipment manufacturers need to work co-operatively to develop test methods that evaluate the reliability and expected performance of remanufactured components.
- Developing parts reliability databases to provide enough information on specific part design to allow reuse without extensive testing.
- Developing low-cost parts tracking technology to provide a method for dismantlers to sort reusable parts from scrap.

The greatest impact for enhancing the reuse and remanufacturability of products can be achieved in the initial design stages. However, current methodologies in these areas are lacking, especially in quantitative decision support metrics [Amezquita 95]. Shu et al. [Shu 95] presented a remanufacture cost model for a toner cartridge and compare the fastening methods that are used in a number of case studies with alternative fastening methods. Their cost model incorporates cost and time variables related to disassembly and assembly as well as probabilistic failure estimations of various parts and fastening methods. Amezquita et al. [Amezquita 95] have proposed a set of qualitative metrics for remanufacturability with emphasis on the ease of disassembly, cleaning, inspection, part replacement, reassembly, reuse components as well as standardisation procedures. It is also recommended that in standardisation, common interfaces and fasteners are used together in a modular framework design.

2.4.4 Design for service

Design for service (DFS) aims to design products that are able to allow for the ease of serviceability as well as for reassembly after service. Much work has been done on DFS by Subramani and Dewhurst [Subramani 91b] and it is an offshoot of the research in Design for Assembly (DFA) by Boothroyd and Dewhurst [Boothroyd 83]. However, there appear to be conflicts between the two approaches as the ease in individual assembly may lead to difficulties in service such as in the elimination of separate fasteners, use of adhesives, use of stacked z-axis assemblies [Boothroyd 83]. Subramani has developed a set of efficiency and cost metrics for serviceability in an attempt to measure the trade offs between rapid assembly and rapid service. This work was based on time and motion study of repair activities involving the elements of part removal, reinsertion, handling and adjustments with data based on the automobile industry [Subramani 92]. This DFS tool has been integrated with Boothroyd Dewhurst Incorporated's (BDI) DFA software to create a tool for designers to estimate post manufacturing costs in the early stages of product development providing estimates of total assembly and reassembly times, and serviceability costs such as labour, operation, part and replacement costs [DFMA 94].

Other models of serviceability have also been approached from an expert system standpoint using the coding of expert knowledge in IF THEN type rules by

Gershenson et al. [Gershenson 91, Ishii 87]. However, a survey by Subramani and Dewhurst indicated that serviceability guidelines may not be directly in a form compatible to expert systems. A data input of 557 rules in a typical industry is run of which 346 rules contained the words "must" or "should" thus resulting in many repeated rules with conflicting forms [Subramani 92].

A Design for Serviceability software tool has been developed by Bryan et al. that addresses the reparability, maintainability and diagnostability within the framework of Serviceability [Bryan 92]. The Service model analysis method was employed to describe which service modes will affect a particular design and in what manner. The output of the tool presents the service cost breakdowns and frequencies in a ranked manner, serviceability indices are displayed and design remarks shown were developed from the serviceability design guidelines.

2.4.5 Conclusions

Design for 'X' methodologies will continue to contribute towards the wider scope of sustainable product development. In future product development more emphasis will be put on questions regarding needs and wants, the required functions as well as environmentally oriented ways to meet such demands. The issues surrounding elementary needs, life cycle design, product systems and long term resource availability and natural compatibility will be central to sustainable product development [van Weenen 95].

DFX tools appear at present to apply only to specific life cycle stages therefore lack an overall integration across the entire life cycle of a product. Most rely on either qualitative check lists or intuitive point scoring systems which may not be sufficient to solve trade-off relations. The major hindrance in the development of a credible analytical tool is the lack of reliable data on materials, parts and components. There appears to be an over emphasis in current product oriented approaches on issues such as waste problems, take back, disassembly and recycling and this is reflected in the overall richness in the methodologies researched in these areas. However, particularly lacking are design integration of quantitative methods to support reuse and remanufacture in electronics products. This is perhaps in part due to the public perception of "used is inferior" attitude and also in part due to the lack of second markets for such products. Although designers play an important role in defining and solving design problems, societal values have equally strong influence over product acceptance. Design changes for promoting sustainable product development may well have to be accompanied by changes in behaviour [Keoleian 96].

2.5 Conclusions for chapter

The review has addressed a number of pertinent environmental issues that face the electronics industry. It has shown that complex interactions exist within the boundary of any environmental framework and particularly highlighted those between legislation, technology and business. Consideration of the drivers shows work should focus on the design undestanding required to allow product life extension and also examine strategies that address the reprocessing of used products.

CHAPTER 3

Issues in product design: An end-of-life product management perspective

3.0 Introduction

This chapter explores design issues related to the end-of-life management of products. Escalating landfill prices as well as impending environmental legislation such as "take back" and "polluter pays" have contributed to the heightened awareness in managing products that have reached their end-of-life. It is widely perceived that the most ecological way to deal with EOL products is to recycle them. However, it is rarely possible to recycle the complete product, what is important in the recycling process is to maximise the recovery of the material contents of a product and to handle the remaining wastes in an ecologically responsible way i.e. by reducing mass and pollution.

One way of realising this is by developing more efficient techniques for disassembling, separating and sorting materials [Clegg 94]. Current materials recovery practise normally involves shredding the product into smaller fragments which are further separated by physical and chemical means. Disassembly however consists of a more organised procedure of materials separation such as salvaging reusable components and subassemblies and more importantly encourages a better isolation of hazardous substances. A significant amount of general work involving disassembly studies have been reported in this thesis and can now be considered at the conceptual phase of the product [Zhang 96]. Design for disassembly (DFDA) methodologies as such are relatively new compared to their more established compatriots - Design for assembly (DFA) methodologies. The chapter will begin by examining the drivers for each of the two methodologies and will also identify some of the conflicts between DFA and DFDA techniques within the current context.

This is followed by an example study of a desktop telephone where the product is dismantled and an initial disassembly assessment performed. This section will give an overview of the design issues surrounding the internal layout of a simple desktop telephone and will highlight both the good and less desirable design practices from the end-of-life perspective. The core issue of the chapter will present a benchmarking case study of eight telephones from European (UK and Germany) and Far Eastern suppliers (China and Malaysia) to establish their suitability for EOL reprocessing. The case studies have led to the development of telephone specific rules for EOL processing, with particular emphasis on disassembly, recycling, remanufacture and resale options. The rules developed are also applied to a pager telecommunications device where miniaturisation technology (often associated with compact electronic equipment such as the pager) is contrasted with the less technology intensive desktop telephone product. The impact of design changes of the telephones to improve EOL practises on manufacturing costs in Europe and the Pacific Rim is next examined based on case studies carried with out with two companies - one in Malaysia and the other in Wales.

The chapter closes by drawing on conclusions from the telephone case studies.

3.1 Design for assembly, Design for disassembly and end-of-life management

The active promotion of DFA methodologies in the last decade has led to many success stories of companies both achieving large savings in manufacturing costs and cutting overall production time [Boothroyd 92]. This has also brought about a positive change of attitude with regards to former "over-the-wall" design practises by encouraging more dialogue between manufacturing and design engineers. Optimisation of parts towards a simpler and more robust design, has however remained the crux of these methodologies.

As discussed in chapter 2, design for disassembly on the other hand arose out of environmental concerns and legislative pressures. Current work in electronic disassembly addresses two important issues: (i) that of relieving the urgent need to deal with present end-of-life products, and (ii) provide a foundation for future development of disassembly methodologies. The apparent conflict appears to be one between high efficiency design and environmental stewardship. For example, in the case of using separate fasteners, DFA techniques recommend the use of rivets while DFDA guidelines propose a threaded fastener, both of which dictate conflicting preferences [Subramani 91]. It may be argued that though the reduction of parts and prescribed fastening methods from a DFA analysis would reduce significant manufacturing costs and resource savings, these savings could be well translated to costly downstream recycling expenditure as the initial design may discourage efficient disassembly, material separation or remanufacture strategies.

Design and manufacturing trends	Environmentally sound features
Easy assembly	Easy disassembly
Integrated components	Easy repair
Smaller production series	Universality of parts
Shorter production runs	Universality of parts
Lightweight materials	Easy recyclability
Diverse, tailor-made materials for specific applications	Smaller variety of materials

Table 3.0 Potential conflicts between trends in design and manufacturing and environmentally sound waste management

DFMA Checklist [adapted from Leaney 92]	Contribution to ease of assembly of Proprinter	Contribution to ease of disassembly of Proprinter
Simplicity of design	Y	Y
Use of standard materials and components	Y	Y
Rationalise product design across product families and modules	Y	Y
Use of widest permissible tolerances	Y	Y
Teamwork (i.e. concurrent engineering, training)	Y	Y
Reduction of non-value added operations (i.e. re-orientation, inspection)	Y	N
Good process planning (i.e. design surface finish into injection moulded parts, include non-functional elements to aid feeding and orienting, etc.)	Y	N
Materials chosen to suit function and production processes	Y	N

Table 3.1 Comparison of DFMA measures against the ease of disassembly in the design of the IBM Proprinter

Despite other incompatible goals of recent manufacturing philosophies with that of green engineering (see table 3.0), the influence of good DFA design to the ease of dismantling and serviceability appear to be correlated and cannot be ignored in most practical applications. This is illustrated in table 3.1 by the redesign of the IBM Proprinter using DFMA principles against the ease of disassembly of the printer. It indicates that products which are easy to assemble are usually easier to disassemble and reassemble, what is lacking is a clear and structured framework that encompasses both DFA and DFDA considerations at the conceptual design stage. Japanese experience [Clegg 94] also appears to indicate that designs optimised for assembly are difficult to re-optimise for disassembly.

Table 3.2 shows a set of 15 metrics and their place in DFA, DFDA and DFS in an attempt to explore some of the reasons for this and to extend the considerations to sustainable design - perhaps the ultimate goal. The table attempts to identify significant points of consideration for the three aspects of design at the conceptual stage. It can be seen that certain pairs of metrics depict reverse operations (i.e. Uniform assembly direction vs. Uniform disassembly direction), these are not necessarily thermodynamically reversible processes. The effects of corrosion, presence of glue, solder or use of other bonding methods such as welding, ultrasonic fastening, self clinching studs and nuts require effort to separate the components in order to increase the entropy of the materials this echos the use of entropy by Suga et al. [Suga 96]; the extent of thermodynamic reversibility appears to require a trade-off between the conflicting goals of DFA and DFDA.

DFA techniques have well established methods of cost-based analysis while disassembly methods are presently being developed in this respect. The costs estimated for designs optimised for both DFA and DFDA may not equate to the cost estimate of disassembly and assembly taken independently: the cost economics of reverse operations appear non-commutative with their opposite. One of the reasons could be attributed to the fact that the steps within a DFA analysis tended normally to be solely value added processes whilst in DFDA, selecting an optimal disassembly sequence is

s/n	Metrics	DFA	DFDA	DFS		
				Reuse/ recycling of materials	Remanufacture of components/ assemblies (including down-cycling)	Serviceability/ modular upgrade of products
1	Reduction of parts	X	X	X	X	X
2	Reduction of assembly operations	X	X	X	X	X
3	Standard components and materials	X	X	X	X	X
4	Reduction of non-value added operations (i.e. re-orientation, inspection)	X	X			
5	Widest permissible tolerances	X			X	X
6	Quantitative measurers of operations (i.e. cost calibration, performance indices/ ratios, etc.)	X	X	X	X	X
7	Uniform assembly/ disassembly direction	X	X	X	X	X
8	Non-ageing/ corrosive material combination		X	X	X	X
9	Joining elements easy to separate or destroy (i.e. use snap fits, avoid inserts)		X	X	X	X
10	Reduce materials count	X	X	X	X	
11	Easy access and good visibility at separation points		X	X	X	X
12	Avoidance of hazardous materials			X	X	X
13	Durability of materials			X	X	X
14	Good identifiability and separability of materials		X	X	X	
15	Clean manufacturing (i.e. reduction of total waste emission and system energy)			X	X	

Table 3.2 Metrics comparison for Design for assembly, Design for disassembly and Design for sustainability at the conceptual design stages of product development.

** X denotes point considered in the design process usually the goal to balance between disassembly expenditure and potential revenue from the recovery of components and materials [Zhang 96]. Other quantitative measures such as cost calibration, performance indices and ratios are also found lacking in issues dealing with the reuse/ recycling of materials, remanufacture of components/ assemblies and serviceability/ modular upgrade of products. Whilst the grouping of metrics 1 to 11 represents a general checklist for DFA/ DFDA goals, it can be seen that DFA requires extension by metrics 9,10, 11-15 while DFDA requires extension by metrics 5, 12, 13, 15. The challenges for particular routes that map DFA to DFS are mainly directed towards material issues; these, though rarely represented in current DFA systems, are embodied within metrics 12 to 15. This work is reported in an earlier publication by the author [Low 94a].

3.1.1 Summary

DFA should not be seen to be in conflict with current DFDA methodologies; these two techniques are being drawn together towards a common goal within the life-cycle design concept. There are indications that the present generation cost models of assembly and disassembly operations may be generally non-commutative, this could be attributed to the extent of thermodynamic reversibility of the assembly/ disassembly operation, in part distinguished by the use of various bonding methods, process of material ageing, rust and contamination and in part due to the financial goals of each methodology; the former focuses on reducing manufacturing costs by optimising every step into a value added process whilst the latter is concerned with selecting an optimal disassembly sequence to balance between disassembly expenditure and potential revenue from the recovery of components and materials.

Following this general discussion of DFA and DFDA methodologies, we now turn to an example study of a desktop telephone in order to further explore a more specific disassembly problem as well as related design issues from the end-of-life perspective.

3.2 Example study of a desktop telephone

This section now focuses on an example study of a typical desktop telephone to assess its ease of disassembly, materials recycling and remanufacture. The initial design/ disassembly assessment is summarised in a table of design features. The detailed explanation follows will attempt to give an overview of end-of-life issues specific to desktop telephones.

3.2.1 Introduction

The traditional leasing of telephones and the return of them in sufficiently large quantities has provided an infrastructure that has been tolerably successful in providing a materials recovery scheme - mainly focused on recycling of the acrylonitrile butadiene styrene (ABS) housing [Biddle 94]. Other materials that are recycled include jack plugs for their gold content, some electronic chips from PCBs (handset transducers are also recycled in burglar alarms) as well as the recovery of gold in printed circuit boards. While telephone cords are considered scrap items, batteries which contain cadmium, lithium, manganese and other toxic substances have recognised routes for safe disposal.

The Relate 300 telephone model is used to illustrate the construction of a typical desktop telephone and how its design could affect EOL reprocessing in the areas of disassembly, materials recycling and remanufacture. Strong and weak design features are assessed and design changes are suggested, and in certain cases illustrated using examples found in other telephone products.

Table 3.3 depicts an initial design assessment by dismantling the Relate 300 to determine the ease of disassembly of the product. The assessment of disassembly operation is normally one of the first steps in EOL reprocessing; a product which can be easily disassembled is also likely to encourage the ease in materials separation which, in the case of the telephone handset, is particularly vital for plastics recycling.

Design/ disassembly assessment of Relate 300

Strong design features

(1) Only paper labels used.
(2) Detachable wire connections between speaker, battery compartment, microphone and printed circuit board (PCB).
(3) No screws to secure PCB - moulded plastic pins from base panel double as position guides for assembly.
(4) Rubber feet may be unplugged easily.
(5) Shallow disassembly depth, all parts rigid except for silicone mat.
(6) Presence of materials identification. Internal ABS coding.
(7) Rubber that encapsulates mouthpiece microphone also doubles as weights - does away with the need for separate metal/ plasticine weights.

Weaker design features

(8) Line and handset cord plugs at base panel lack open access - access restricted by presence of base stand.
(9) Additional screw to secure battery compartment. Also contains metal threads.
(10) Dual colour plastic mixes for numeric keypads.
(11) Total of 8 screws used:
- 4 to secure base to front panel
- 1 screw to secure batteries to compartment
- 2 screws to secure speaker
- 1 screw to secure handset

(12) Push in cord plugs difficult to pull out.
(13) Plastic numeric keypads difficult to disassemble.
(14) Following parts form permanent joints:
- 2 perspex LED windows welded to front panel.
- Tone caller ultrasonically welded into position.
- Perspex LCD window glued to front panel.

(15) LCD unit difficult to disassemble from PCB.
(16) Difficult to separate snap fit that holds handset together.
(17) Backing paper under clear window on top panel contribute to material mixes.
(18) Product logo spray painted onto top panel causes plastic contamination.

Table 3.3 Design/ disassembly assessment of Relate 300

A more detailed explanation is offered below for each of the remarks in table 3.3.

(1) Only paper labels used

One of the major barriers to clean plastics recycling is the presence of contaminants such as adhesive labels (both metallic and paper) and glue. The current practise is to remove them manually, a time consuming operation in itself depending on the extent of the adhesive and other contaminants. The residual contents are then removed using a filtration process. Although paper labels are less contaminating than metallic stickers (since they are vapourised more easily), a better alternative is to mould in labels or if adhesive labels are required, mono coloured prints are preferred.

(2) Detachable wire connections between speaker, battery compartment, microphone and printed circuit board

The internal wire connections of the Relate 300 are detachable by adopting the use of wire clip connectors instead of using conventional soldered connections. Although this is helpful from the seviceability point of view, an alternative approach is to eliminate many as possible if not all wire connections. This may be done by designing all the electrical and electronic components to fit onto a single printed circuit board. The advantages are two-fold: firstly it saves additional disassembly time and labour, secondly it promotes a better materials separation.

(3) No screws to secure PCB - moulded plastic pins from base panel double as position guides for assembly

Reducing the total number of screws in a product is always a positive design feature as it cuts down disassembly time and costs. The advantage of using moulded plastic pins as position guides for the PCB is that it holds the entire subassembly in place without additional screws but "falls apart" once the top casing is removed. This facilitates the separation of component parts quickly.

(4) *Rubber feet may be unplugged easily.*

The prime function of the rubber feet is to satisfy the '5 seconds no-slip requirement' on glass when the phone cord is extended to 1.7m from the base unit. They are secured without the use of additional materials such as glue or screws. Since they could be unplugged easily with no residual precipitate, it promotes a purer feedstock towards the recycling of the ABS plastic.

(5) *Shallow disassembly depth, all parts rigid except for silicone mat*

Shallow disassembly depth promotes easy access to parts, this is a good criterion for serviceability. In a dismantling operation rigid parts are easier to handle than flexible parts, an example would be the silicone mats in the base unit for electrical contacts between the key pads and the PCB. Reducing parts/ subassemblies that are flexible is desirable since they enable easier handling during and after the dismantling process.

(6) *Presence of materials identification. Internal ABS coding.*

The presence of identification is important for effective materials separation, this is particularly so in the recycling of plastics where the quality of the recyclate is largely determined by the feedstock purity rather than by process conditions. In the Relate 300 example, internal ABS codings (complete with a clear time stamp) were moulded onto all the plastic casing. However, it is felt that the adoption of an internationally recognised coding system such as the ISO system could be more useful, especially if the plastics are to be reprocessed by third party vendors.

(7) Rubber that encapsulates mouthpiece microphone also doubles as weights - do away with the need for separate metal/ plasticine weights

To provide a correct "feel" to the weight of the handset, additional weights in the form of small rectangular metal ingots are normally mounted to the casing via screws and/or glue*, this is clearly an additional disassembly burden (see figure 3.0). The handset of the Relate 300 is designed with an encapsulating rubber casing around the microphone mouthpiece which in itself doubles as a weight that holds the assembly without the use of screws. The whole handset subassembly is dismantled quickly once the snap fit holding the top and bottom casings are separated. figure 3.1 illustrates the improved handset design of the Relate 300 without the lead weights.

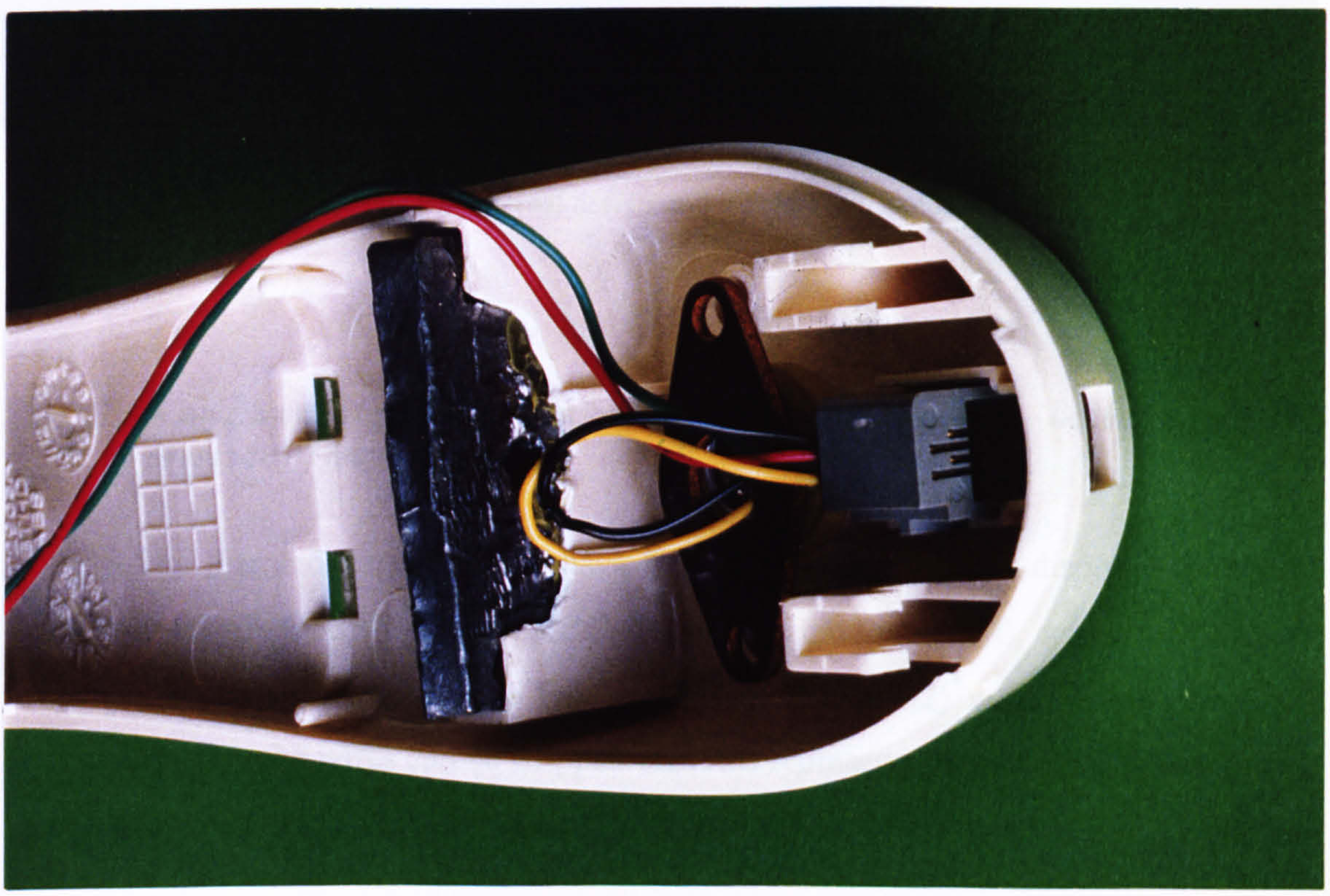

Figure 3.0 A conventional weighted handset with lead ingot secured to the casing by glue

*This is in accordance with the British Telecom corporate standard product design guidance on best practice. The recommended handsets of 2 piece corded phones should weigh 185g, centre of gravity 4mm south of centre. Telephone base minimum weight should be 350g. There also appears to be no prohibition of the use of adhesives for fixing "minor" parts such as weights.

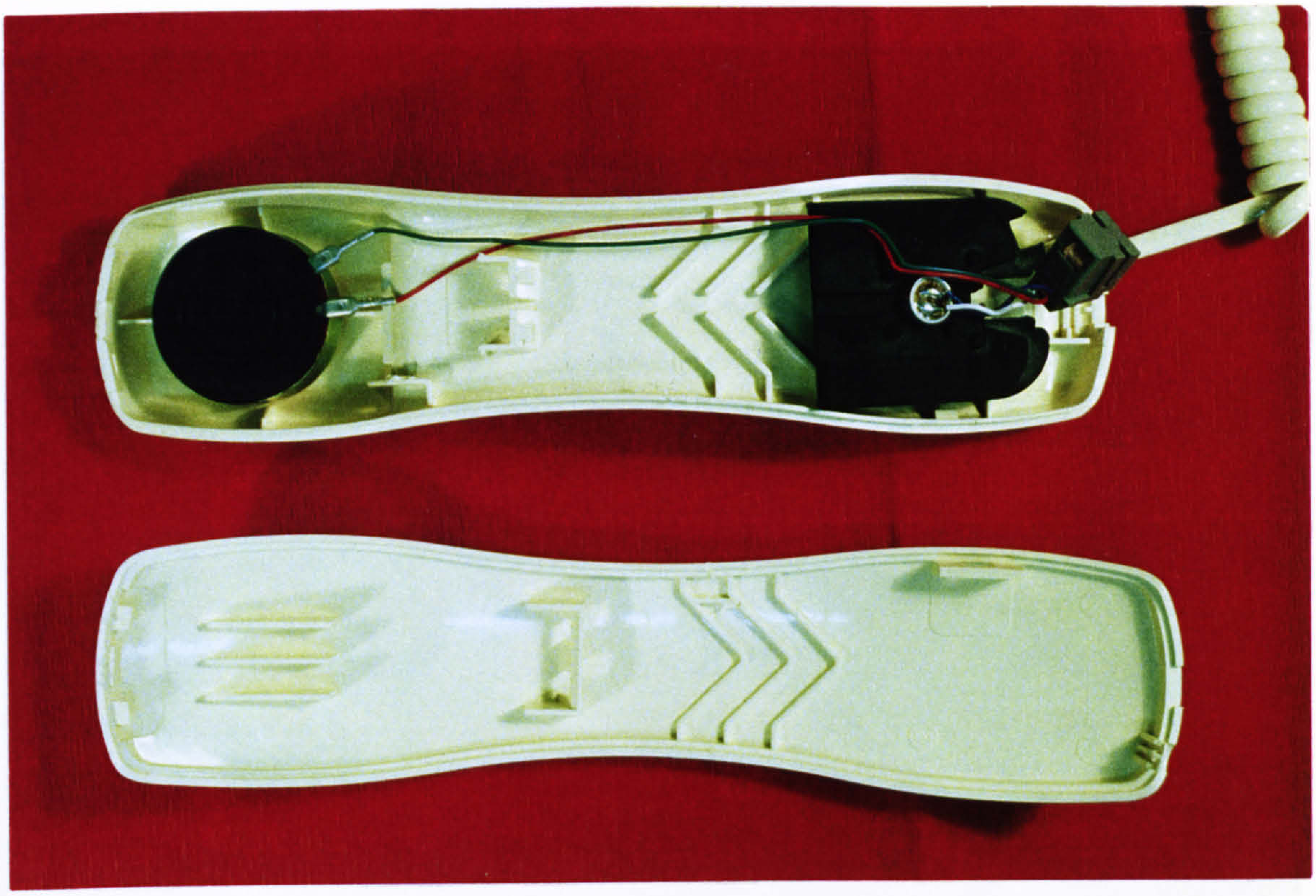

Figure 3.1 Internal design of the Relate 300 handset

(8) Line and handset cord plugs at base panel lack open access - access restricted by presence of base stand.

The line and handset cords have little scrap value and are disposed of when they are separated from the base unit. In the case of the Relate 300, access to the line/ cord plugs are restricted by the base stand (see figure 3.2) which has to be first removed before the wires can be stripped off. This represents an additional disassembly step which may be corrected by re-designing the base for easy access.

Figure 3.2 Presence of base stand restricting access to the removal of the line and handset cords

(9) Additional screw to secure battery compartment. Also contains metal threads.

Metal inserts and threads have to be removed from the battery compartment before the plastic casing can be used for recycling. Figure 3.3 illustrates the design of the battery compartment before the metal inserts are removed. The current practise requires first separating the battery unit from the base casing and followed by the metal inserts being stripped off manually. The remaining part is then mounted onto a jig for the screw threads to be drilled out.

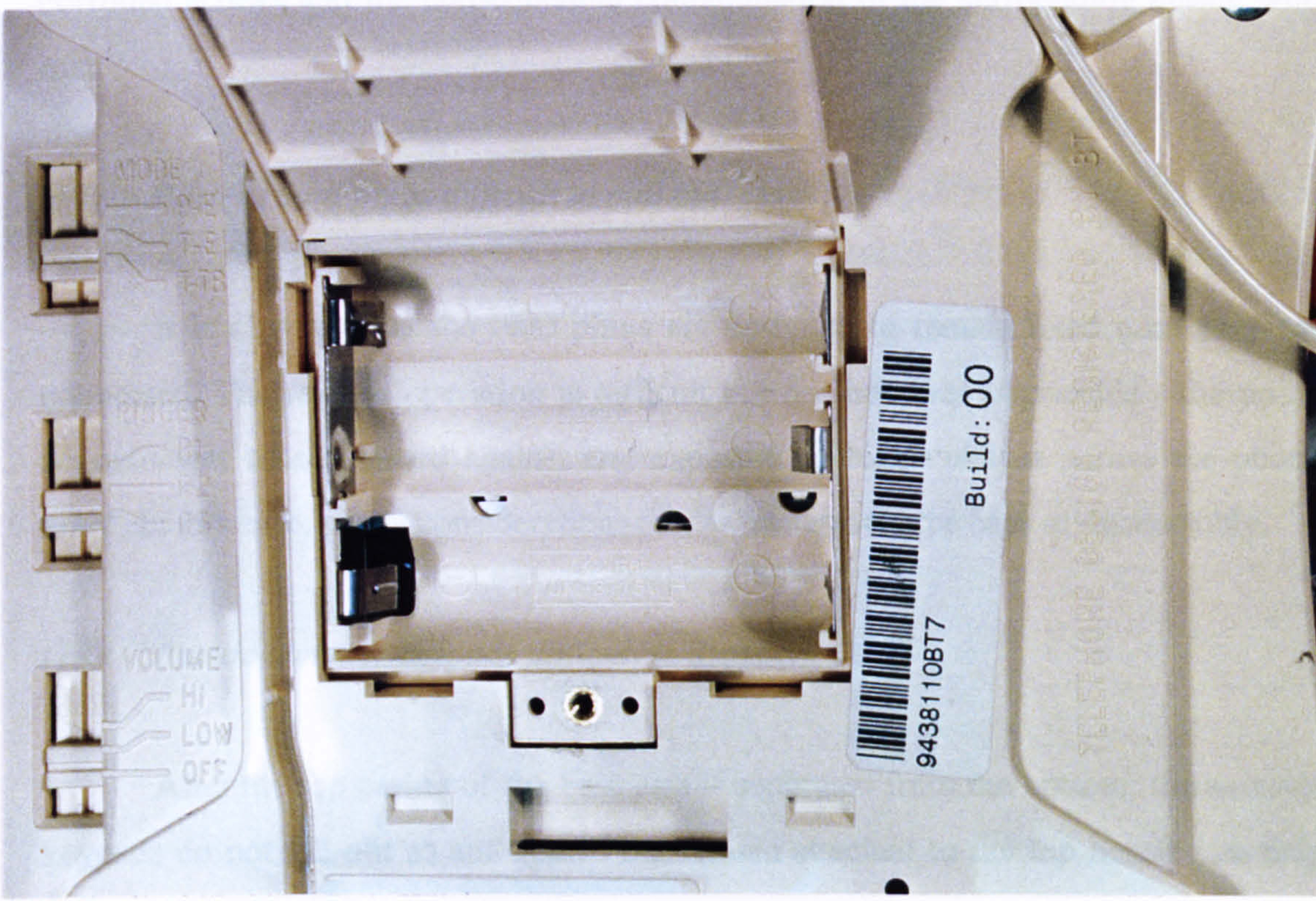

Figure 3.3 Design of the battery compartment consisting of metal inserts and threads which have to be removed prior recycling

(10) Dual colour plastic mixes for numeric keypads.

The numeric keypads are made from co-moulded plastics, this makes practical separation of the light and dark coloured parts difficult; they are normally recycled as mixed plastics. In practise, the recyclate from a mixed coloured feedstock is normally dyed to a darker colour. However, should the feedstock be from a mixture of different plastic types, recycling them will not be of practical use as the chemical properties of the final product does not normally remain consistent and predictable.

(11) Total of 8 screws used - needs further reduction

Reducing the total number of screws used is one of the major criteria for quick disassembly of a product, this criteria also is in no doubt an important rule in optimising a design for assembly. Although the use of screws appear to be a secure method for fastening, there are disadvantages such as the difficulty in removing corroded screws and the consequential contamination of the surrounding plastic with rust.

(12) Push in cord plugs difficult to pull out

It is obvious that the cord plugs are designed to remain fixed once they are connected. The reverse operation is difficult but not however impossible - the prime concern was to safe-guard against any exposure to high voltages across the phone lines*. In this case, safety considerations predominates over the ease of disassembly.

(13) Plastic numeric keypads difficult to disassemble

After the top casing of the base unit is separated from the bottom, the numeric keypads do not fall out as anticipated but remain attached to the top housing as they are restricted by J hooks. The base unit was assembled from the bottom up i.e. components are assembled from the bottom casing upwards. The use of J hooks is effective from the assembly viewpoint as they prevent the numeric keypads from accidentally falling out in the assembly process. However, this design does not appear to be equally attractive from the disassembly point of view as it makes removal of the numeric keypads difficult - extra labour time is required to manually separate the keypads for any cleaning as well as stripping off the other remaining components such as the perspex LCD window before the housing is ready for recycling.

(14) Following parts form permanent joints: 2 perspex LED window welded to front panel, Tone caller ultrasonically welded into position, Perspex LCD window glued to front panel

Removing contaminants to encourage feedstock purity is the prime concern here. If components of a foreign material are required to be attached, other clean non-permanent fastening methods should be employed such as using removable brackets, snap fits, etc.

*This is a UK practise only as dictated by design standards.

(15) LCD unit difficult to disassemble from PCB

The LCD unit is mounted onto the PCB via a metal housing with legs secured through custom slots (via a twist-lock action) to the circuit board. Due to the toxicity of chemicals present such as indium-tin oxides in the liquid display panel, disposal of the unit through controlled channels requiring complete combustion is needed to prevent the formation of dioxins. The present design does not offer quick dismantling of the unit as the legs of the metal brackets must first be manually "untwisted" to release the display from the PCB.

(16) Difficult to separate snap fit that holds handset together.

Two halves of the handset are secured via a safety screw and are snap fitted together. However, due to the tight tolerance of the snap fit, it is difficult to separate the two halves once they are assembled.

(17) Backing paper under clear window on top panel contribute to material mixes.

The backing paper must first be removed as it is a contaminant to the ABS feedstock. This again represents an additional disassembly step.

(18) BT logo spray painted onto top panel causes plastic contamination.

The use of spray paint should be avoided as it represents an impurity for the ABS feedstock.

The above example study of the Relate 300 has highlighted salient points for consideration in the upstream design of a typical product for downstream disassembly, materials separation and recycling. Although there are several design features that are telephone specific, the assessment at this stage appears to indicate that the disassembly function is important for components and materials separation for further reprocessing. The criteria for quick disassembly may however be in conflict with conventional design-for-assembly methodologies as well as with other less tangible aspects related to safety issues. Since recycling of the ABS plastic remains one of the major reprocessing operations for telephone products, minimising material mixes to encourage a purer feedstock appears also to be an important design consideration although the major constraint lies in plastic recycling process technology as well as in specification requirements.

The following section will explore in further detail several telephone handsets and establish their suitability for disassembly and recycling as a benchmark of designs for disassembly and environmental legislation and also to create a framework of rules for DFDA, particularly for telephones.

3.3 Comparative case studies of eight telephone handsets

This section presents a comparative case study of eight telephones from European suppliers (UK and Germany) and Far Eastern suppliers (China and Malaysia) to establish their suitability for disassembly and recycling. Europe is at the forefront of environmental technologies whilst the Pacific Rim predominates as a manufacturing hub but with less environmental critical technologies. Similar products designed in both areas reflect differences driven by different levels of environmental concerns and manufacturing conditions. This presents an unique scenario to investigate the impact of design changes to improve the end-of-life practises on manufacturing costs in Europe and the Pacific Rim within the context of telephone handsets. The opportunities for re-use, remanufacture and materials recycling have been identified such that the maximum of added value is retained.

3.3.1 Design rules and disassembly assessment

Eight office desktop telephones with broadly similar functions were used in the case studies:

Telephone model	Country of manufacture (manufacturer)	Remarks
Relate 100	UK (Nortel)	For BT approved use
Relate 300	UK (Nortel)	For BT approved use
Relate 180	UK (Nortel)	For BT approved use
Duet 200	Malaysia (Inventec)	For BT approved use
Converse 300	Malaysia (Inventec)	For BT approved use
Dialatron Call Timer	China (Not known)	For BT approved use
Euroset 802	Germany (Siemens)	Not for sale in the UK
Euroset 812	Germany (Siemens)	Not for sale in the UK

The telephones were first manually disassembled into their component parts and sub-assemblies. A qualitative assessment of the difficulties encountered in the dismantling process (similar to the earlier example study of the Relate 300) was performed for each phone unit. The results of the assessments, excluding the Relate 300 telephone set, are summarised in tables 3.4 to 3.10.

Design/ disassembly assessment of Relate 180

Strong design features

(1) No paper labels. BT "green dot" now moulded into base.
(2) No LCDs.
(3) Few parts, all rigid except for silicon mat.
(4) No screws to secure PCB to base panel.
(5) Base rubber feet can be removed.
(6) Presence of material identification (ABS). Internal coding.
(7) All electronic/ electrical components on single PCB.
(8) Base stand easily removed. Open access to line jacks.
(9) One silicon mat assembly only.
(10) Numeric key pads easily removed.
(11) Perspex LED window can be detached from body.

Weaker design features

(1) Push-in plugs difficult to pull out.
(2) Total of 7 screws used:
- 4 for base unit
- 3 for handset
(3) Numeric keypads contain plastic mixes of different colour.
(4) BT logo hot-stamped on front panel.

Table 3.4 Design/ disassembly assessment of Relate 180

Design/ disassembly assessment of Relate 100

Strong design features

(1) Only paper labels used.
(2) No LCD in PCB.
(3) Few parts, all rigid except for silicone mats.
(4) No screws to secure board assembly onto base panel.
(5) Base rubber feet can be removed.
(6) Presence of material identification (ABS). Internal coding.
(7) Plastic mould that encapsulates microphone in handset also doubles as weight.
(8) Board assembly not heavily populated.

Weaker design features

(1) Base stand assembly prevents open access to line/ handset cord plugs.
(2) Numeric keypads contain dual colour plastic mixes (co-moulded polymer).
(3) Tone caller glued along rim to bracket.
(4) Total of 5 screws:
 - 4 for base unit
 - 1 for handset
(5) Push-in plugs difficult to pull out.
(6) Difficult to dismantle the two halves of the plastic moulded handset.
(7) BT logo & other numbers spray painted onto body (plastic contamination).

Table 3.5 Design/ disassembly assessment of Relate 100

Design/ disassembly assessment of Duet 200

Strong design features

(1) Material identification present ABS body.
(2) Paper labels used only.
(3) LCD display not secured to board assembly, easily separated and disposed.
(4) Keypad pop-fits are removable from body however they contain co-moulded plastics.

Weaker design features

(1) Total of 21 screws:
- 8 for base assembly (4 c/w washers)
- 10 for top body panel
- 3 for handset

(2) Reset handle bar design obstructs access to 2 screws on board assembly.
(3) Metal weights are secured to base assembly by screws and glue.
(4) Sticky tape that secure wires will cause plastic contamination if left unremoved.
(5) LCD protective plastic window glued onto body.
(6) BT logo & other numbers spray painted onto body.
(7) Push-in plugs difficult to pull out.
(8) Handset
- Plastic moulding encapsulates earpiece with glued on foam padding.
- Metal weight glued to slot.
- External perspex window with backing paper adds to extra material separation.
- Process label stickers (paper) on handset (behind backing paper).

(9) Rubber feet pads glued onto base of phone.
(10) Base stand prevents open access to line/ handset cord plugs.

Table 3.6 Design/ disassembly assessment of Duet 200

Design/ disassembly assessment of Converse 300

Strong design features

(1) Material identification present on ABS body.
(2) LCD display not secured to board assembly, easily separated.
(3) Numeric keypads are easily removable from body however they contain co-moulded plastics.
(4) Paper labels used only.
(5) Battery cover not secured by extra screws.

Weaker design features

(1) Base stand prevents open access to line/ handset cord plugs.
(2) Total of 26 screws used:
  - 7 on base panel (3 alone for battery compartment)
  - 11 on board assembly
  - 3 on internal speaker
  - 2 on tone caller
  - 3 on handset
(3) All wire connections are soldered (instead of flying leads) , must cut wires to access keypads below board assembly.
(4) LCD protective plastic window glued onto body.
(5) Use of sticky tape to secure LCD onto frame. Contributes to extra material separation and may also contaminate ABS if left unremoved.
(6) BT logo & other numbers spray painted onto body.
(7) Spring/ metal inserts in battery compartment.
(8) Rubber feet pads glued onto base of phone.
(9) Push-in plugs difficult to pull out.
(10) Handset
  - Hidden access to screw.
  - Metal weight difficult to remove.
  - Foam pads glued onto back of earpiece, difficult to recondition item for reuse.

Table 3.7 Design/ disassembly assessment of Converse 300

Design/ disassembly assessment of Dialatron Call Timer

Strong design features

(1) Base unit has no electronic components - less disposal hazard.
(2) Numeric keypads are easily removed.
(3) One silicone mat assembly only.
(4) LCD protective window not glued onto frame.

Weaker design features

(1) Total of 26 screws:
- 1 on handset: top to base assembly only
- 4 on handset: top board assembly only
- 10 on handset: base assembly only
- 2 on handset: earpiece
- 9 on base unit

(2) LCD unit secured onto board assembly by solvent melted plastic legs.
(3) Glued parts:
- Tone caller (handset) to bracket.
- Tone caller (handset) wires to body.
- Handset microphone to bracket
- Earpiece foam paddings to earpiece bracket.
- Rubber feet pads to base.

(4) Absence of detachable cord plugs - leads connected directly to PCB.
(5) Metal weights screwed onto base.
(6) Subassemblies connected by soldered leads.
(7) Combination of plastic mixes to be separated from base unit.
(8) Metallic stickers used in handset.
(9) No noticeable material identifications.
(10) Spray painted logo on handset.

Table 3.8 Design/ disassembly assessment of the Dialatron Call Timer

Design/ disassembly assessment of Euroset 802

Strong design features

(1) Presence of 1 paper label (matt finish, single colour)
(2) Few parts, all rigid except for silicone mat.
(3) No screws to hold PCB onto base panel.
(4) Base rubber feet can be removed.
(5) Material identification (ABS) present.
(6) Numeric keypads can be removed easily.
(7) Choice of ABS matt surface finish tends to hide moulding flaw and is more dirt tolerant.
(8) All electrical/ electronic items found on PCB. No LCDs.
(9) Push in plugs easy to pull out.
(10) Handset assembled by snap fit. Internal components not secured by screws. Absence of metal weight*.

Weaker design features

(1) Siemens logo and instructions hot stamped onto front panel.
(2) Total of 5 screws used to secure base panel.
(3) Dual colour plastic mixes for numeric key pads.
(4) Earpiece in handset glued onto frame.

Table 3.9 Design/ disassembly assessment of Euroset 802

*This is in contrast with BT phones where the inclusion of weights reflect the industrial design guidelines

Design/ disassembly assessment of Euroset 812

Strong design features

(1) Presence of 1 paper label (matt finish, single colour).
(2) No screws to hold PCB.
(3) Base rubber feet can be removed.
(4) Material identification (ABS) present.
(5) Numeric keypads can be removed easily.
(6) Choice of ABS matt surface finish tends to hide moulding flaw and is more dirt tolerant.
(7) All electrical/ electronic items found on PCB except for handsfree speaker.
(8) Handsfree speaker secured by plastic snap on ring (no screws used).
(9) Push in plugs easy to pull out.
(10) Handset assembled by snap fit. Internal components not secured by screws. Absence of metal weight*.
(11) Wire connections are detachable (not soldered).
(12) LCD unit can be easily removed.

Weaker design features

(1) Siemens logo and instructions hot stamped onto front panel.
(2) Total of 5 screws used to secure base panel.
(3) Dual colour plastic mixes for numeric key pads.
(4) Earpiece in handset glued onto frame.

Table 3.10 Design/ disassembly assessment of Euroset 812

*This is in contrast with the BT phones where the inclusion of weights reflect the industrial design guidelines

The entire dismantling process may range from 30 seconds to less than 2 minutes depending on various factors such as time taken for screw removal, tool change, scrapping of labels, breaking and unsnapping of parts [BT 95a].

The study of tables 3.3 to 3.10 resulted in a list of telephone specific design rules developed for disassembly. Table 3.11 depicts the order of importance ranked by the average time taken for items to be disassembled [BT 95b].

Disassembly rules (Ranked)	
1	Reduce total number of screws to secure sub-assemblies (i.e. use snap fits, mould in parts, etc.)
2	Design numeric keypads to fall out on dismantling.
3	Mount *all* electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible..
4	Avoid using additional (lead/ plasticine) weights in base unit or handset.
5	Avoid the use of glue either as a encapsulator or fastener. Also avoid using sticky/ adhesive tapes to secure wire, components, etc.
6	Design removable rubber feet pads from base unit.
7	Design easily detachable LCD display unit (i.e. use plastic snap-on brackets, adhesive flexible connectors).
8	Use push-in plugs that are easy to pull out.
9	Combine separate silicone button mats into one.
10	Use minimum labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.
11	Use detachable wire connections instead of soldered leads.
12	Design sub-assemblies that have open access for dismantling (i.e. PCB mounting, battery compartments, LCD display unit, etc.)

Table 3.11 Telephone specific disassembly rules

Topping the list is a design check to minimise the total number of screws used. Liberal use of screws as part fasteners were featured in all the Far Eastern products averaging a total of 24 screws. This represents a four fold increase over the European makes which largely secure internal components by innovative housing support - an average of only 6 screw fasteners are used in these handset products. Figure 3.4 provides the pictorial impact of screw fasteners used in both instances. Calculations also revealed that disassembly time for a Far Eastern product is significant in relation to the total disassembly time (57% in the case of Converse 300) and that of a European product (Euroset 802) is about 31% over the total disassembly time [BT 95b].

Figure 3.4 Contrasting the number of screws used in a typical Far Eastern product (left) and that used in a typical European product (right)

There appears to be a design preference of snap fits over screws, on the grounds that snap fits are easier to dismantle. However, it is often actually harder to pry apart snap fits than to remove screws with an air-powered tool - it was found that in certain cases (such as the Euroset 802 and Euroset 812) the time taken to dismantle handsets with snap fits could take twice as long as handsets secured with screws (i.e. Relate 100 and Relate 300).

The design review particularly highlighted that the mounting of all electrical/ electronic components onto the printed circuit board not only eliminated untidy wiring, but has the advantage that it could help to alleviate the effects of space constraints within the housing. This is illustrated by comparing Euroset 802 with Relate 300 in figure 3.5 where the incorporation of the tone ringer onto the PCB in the former relieves the need for separate mounting of a frame and connecting wires to the housing (contrast to in the latter case) and thus effectively provide more free space. However, perhaps more importantly this rule also enables a clean and easy separation of all "foreign" materials from the ABS housing. Three out of five European telephones surveyed have incorporated this feature whereas all the Far Eastern phones lacked this facility.

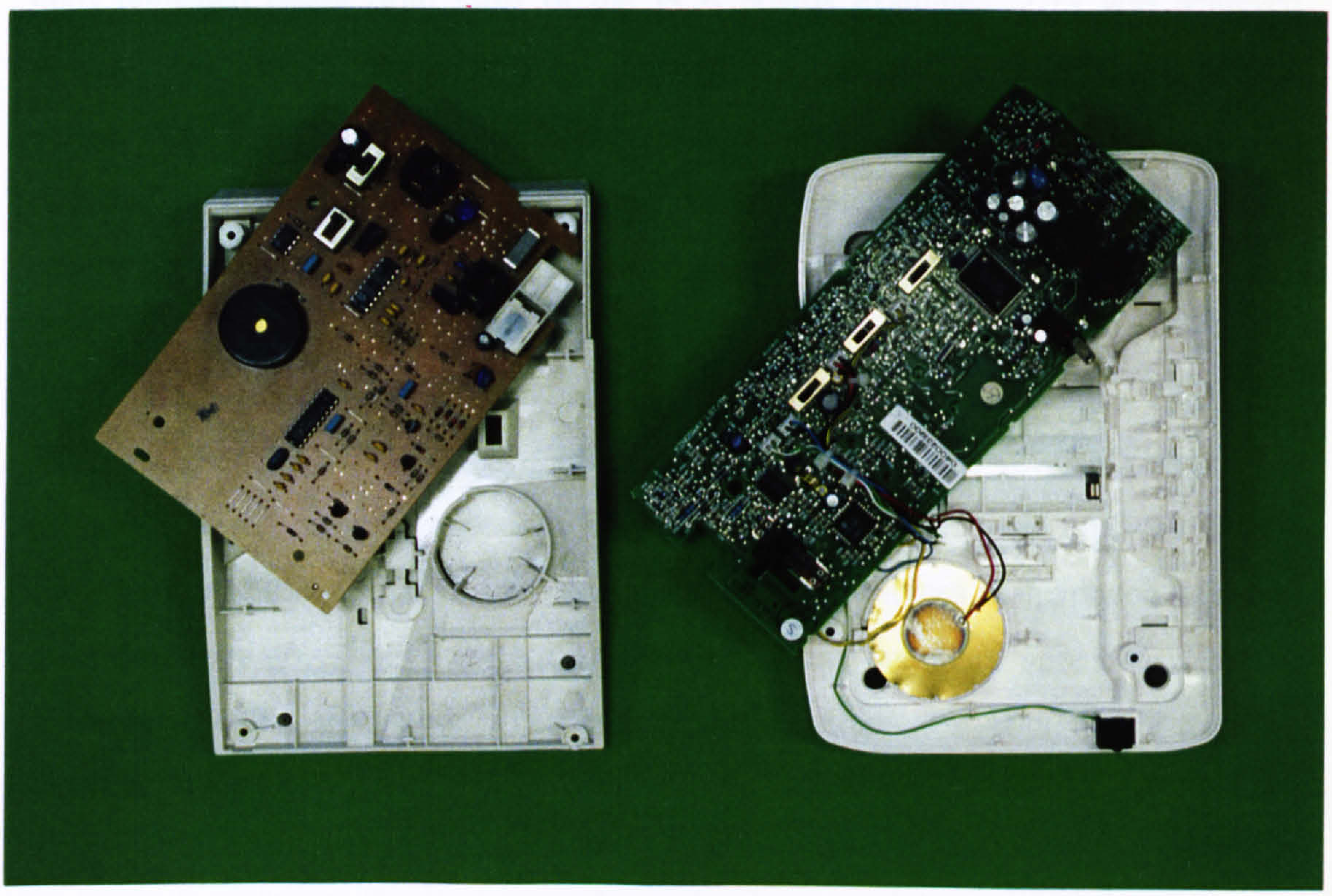

Figure 3.5 PCB layout of the Euroset 802 incorporating all electronic components (left) and PCB layout of the Relate 300 with separate mount for tone ringer and connecting wires (right)

The use of additional weights in base units and handsets are common to all the UK telephone suppliers. The attached weights are usually in the form of small rectangular lead ingots which appear to serve no other distinct functional purpose than to increase the overall weight to provide the correct "feel" for the user. Though the inclusion of weight units are required by British specifications [BT 93], such constraints are not present for the German telephones. The use of lead weights was found to be undesirable for three reasons: (i) it increases disassembly time, especially when the ingots are screwed and secured by glue onto the ABS housing; (ii) there may also be materials contamination; and, (iii) it is ecologically unsound because lead is used.

The design review for disassembly also emphasised that cellophane tapes and glue should be avoided either as a component encapsulator or fastener on grounds of materials contamination. In addition, it was found that the liquid crystal display (LCD) units detached easily from most of the PCB boards examined. This was achieved through the use of plastic snap-on housing brackets and with adhesive flexible connectors. This positive design practise is accentuated by the fact that LCDs encapsulate a mixture of environmentally toxic substances which should be easily removed and disposed through controlled channels.

It was also observed that in the UK, Malaysian and China products, cord plugs were designed to remain fixed once they are connected. The reverse operation is difficult but not however impossible. This is a case showing the requirements of safety over the ease of disassembly - unsafe exposure to high voltages in the phone lines was the prime concern. Though the British and Far Eastern suppliers were bound by UK specifications to manufacture "safety plugs", this requirement is again absent from the German phone units.

The difficulty in the handling of silicone button mats (for electrical contacts between the key pads and the PCB board) is increased due to its construction from a flexible material. A good design practise is to combine smaller separate silicone mats into a single larger one. This results in faster assembly and disassembly times. This feature is absent in the Far Eastern products perhaps in part due to the scattering of the numeric keypad design which causes more than one pad to be used and in part due to the tooling size constraints [Low 95b] as the current tooling setup perhaps does not allow an economical justifiable change*. This can be contrasted to some European models with a dense button placement backed by a single peel away mat bridging a larger non-functional surface area.

The presence of adhesive labels are also detrimental to clean materials recycling. The current practise is to remove them manually and then separate the residual contents using a filtration process. A better alternative is to mould-in labels (as adopted by the newer BT phone designs, see figure 3.6). This represents an improvement over the use of "green dot" stickers in figure 3.7. If adhesive labels are required, mono colour prints are preferred, as demonstrated by the German manufacturers in figure 3.8.

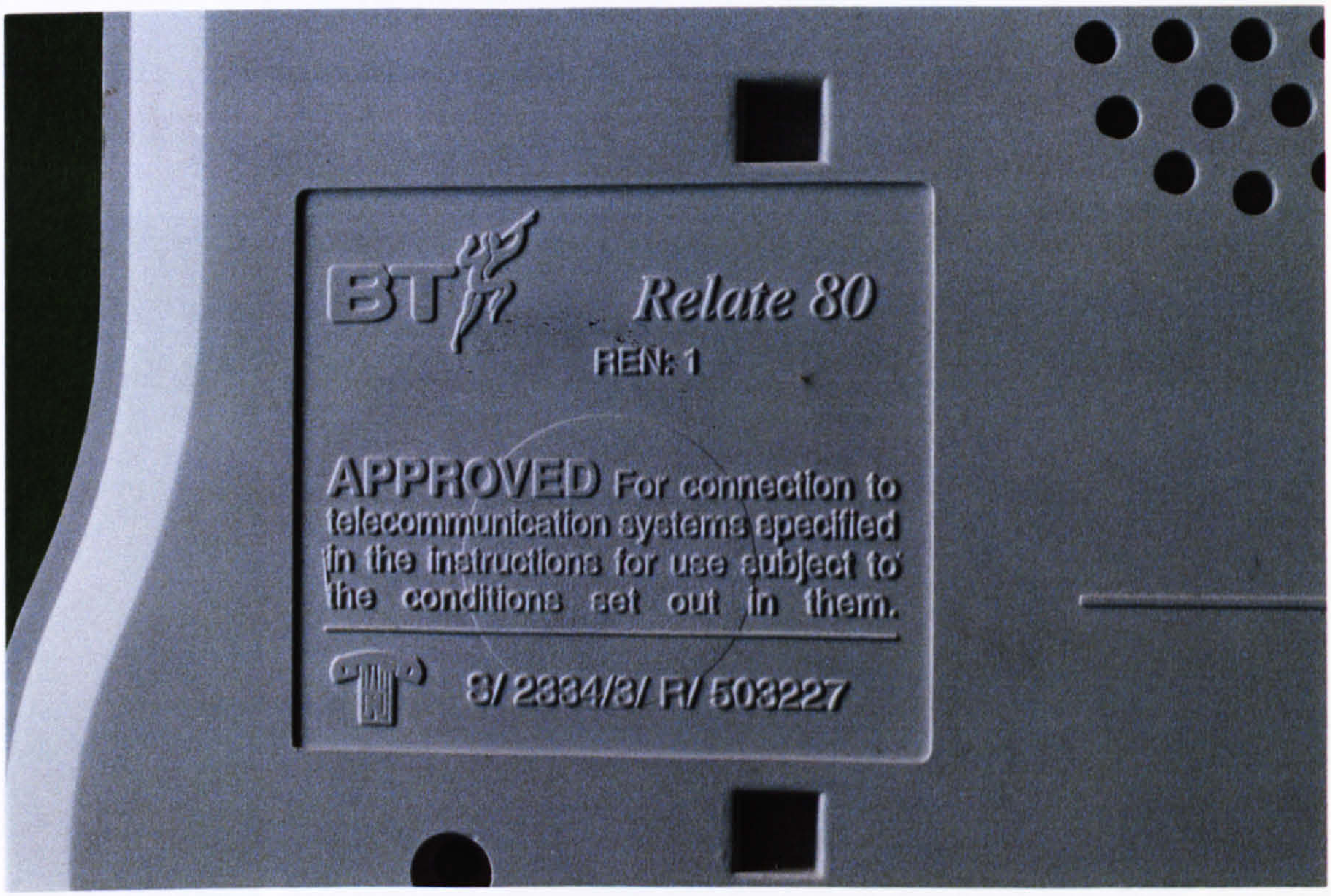

Figure 3.6 Label moulded into ABS base unit

*This point is highlighted in item 9 (table 3.16) in the increase in price estimate against best practise guidelines.

Figure 3.7 Coloured adhesive paper label

Figure 3.8 Mono-coloured adhesive paper label

3.3.2 Design rules for recycling

In developing the rules for recycling, it is necessary to understand the core issues involved in the materials recovery scheme for telephones, one which is mainly focused on the recycling of the ABS housing. Recycled plastics have two main obstacles in their reuse. They must frequently meet stringent requirements for colour matches by the (re)manufacturers: the treatment of off-white telephones for example is problematic due to the high concentration of titanium dioxide which is out of specification with current practise. If plastics are recovered from older electronic scrap, the presence of flame retardants and other additives may prevent further use due to potential infringements of safety regulations - these will have to be either landfilled or incinerated. A better alternative will be to continue recycling the plastics but with addition of virgin stocks to dilute the additive contents.

Recycling/ Materials recovery rules	
13	Use single plastic type throughout (including numeric keypads), preferably in darker colours. Maximise the use of recycled materials whenever possible.
14	Mould in material identification on plastic body.
15	Design PCBs that concentrate high value components.
16	Use matt/ textured surface finish - tends to hide minor moulding flaws better than high gloss finish.
17	Avoid moulding in metal threads/ inserts into plastic body.
18	Minimise the use of spray painted logos.
19	Use mono-colour printed box for packaging. Operator's manual should be concise - if possible limit instructions to one large (folded) double sided page.

Table 3.12 Telephone specific recycling rules

Table 3.12 (rules 13 to 19) also shows a list of telephone specific rules for recycling developed following the design review. The use of a single plastic in dark colours throughout is preferred because it is more tolerant to colour matching. Almost all the products surveyed (apart from the Chinese telephone) had plastic identifications moulded into their housing. It is possible to recycle multi-coloured plastic components provided they are homogenous rather than a mixture of different polymers. In the latter case, the material properties of the mixed constituent plastics are unsatisfactory and are likely to be out of specification after recycling.

The use of a matt or textured surface finish has distinct advantages over a high gloss finish as the former tends to hide moulding flaws and is also less prone to damage - a feature adopted only in the German products. The "Do not use inserts and avoid adhesive labels" rule is also ubiquitous - since both will lead to higher overheads in the disassembly stages. Alternative techniques such as moulding in labels or mechanical attachment are better suited to minimise feedstock impurities. These are demonstrated earlier in figures 3.6 to 3.8.

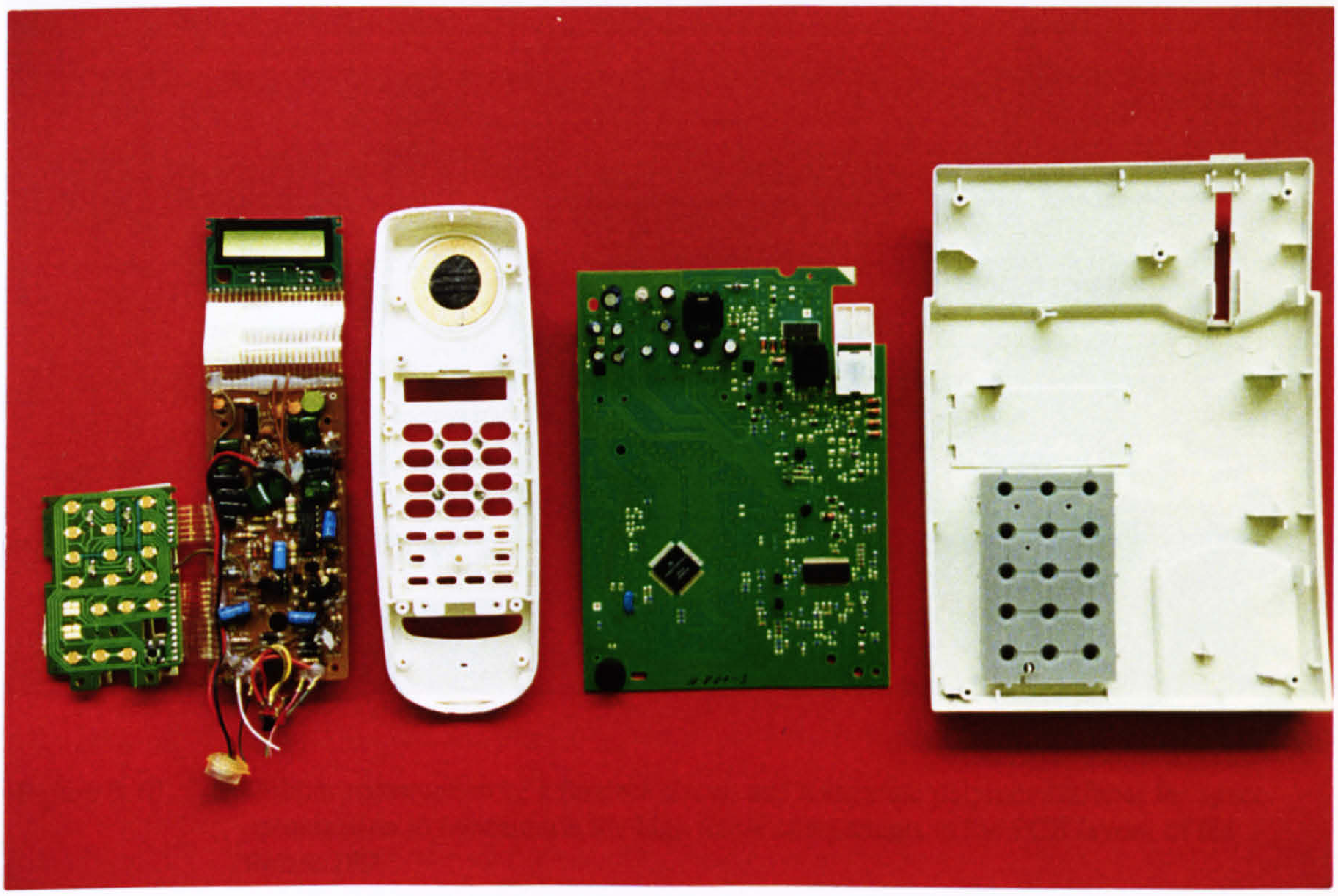

Figure 3.9 Printed circuit board design within the available space in the housing for the Dialatron (left) and the Euroset 812 (right)

The layout of the printed circuit board, the most expensive item of the design, is particularly affected by the external design of the telephone and the space available within the device. Figure 3.9 illustrates an extreme contrast of circuit realisation - printed board design within the space available in the housing for two telephone units.

Small changes in the external design, for example small changes in the height of the internal space, offer considerable potential savings in both manufacturing and end-of-life costs by allowing more imaginative PCB design. A possible board design is to concentrate the location of high value components. This was exploited in the case of Relate 180, a unique construction using a flexible circuit and a separate polymer stiffener (made from recycled material) to give a saving of space and the material used in the PCB manufacturing process. Figure 3.10 illustrates this construction.

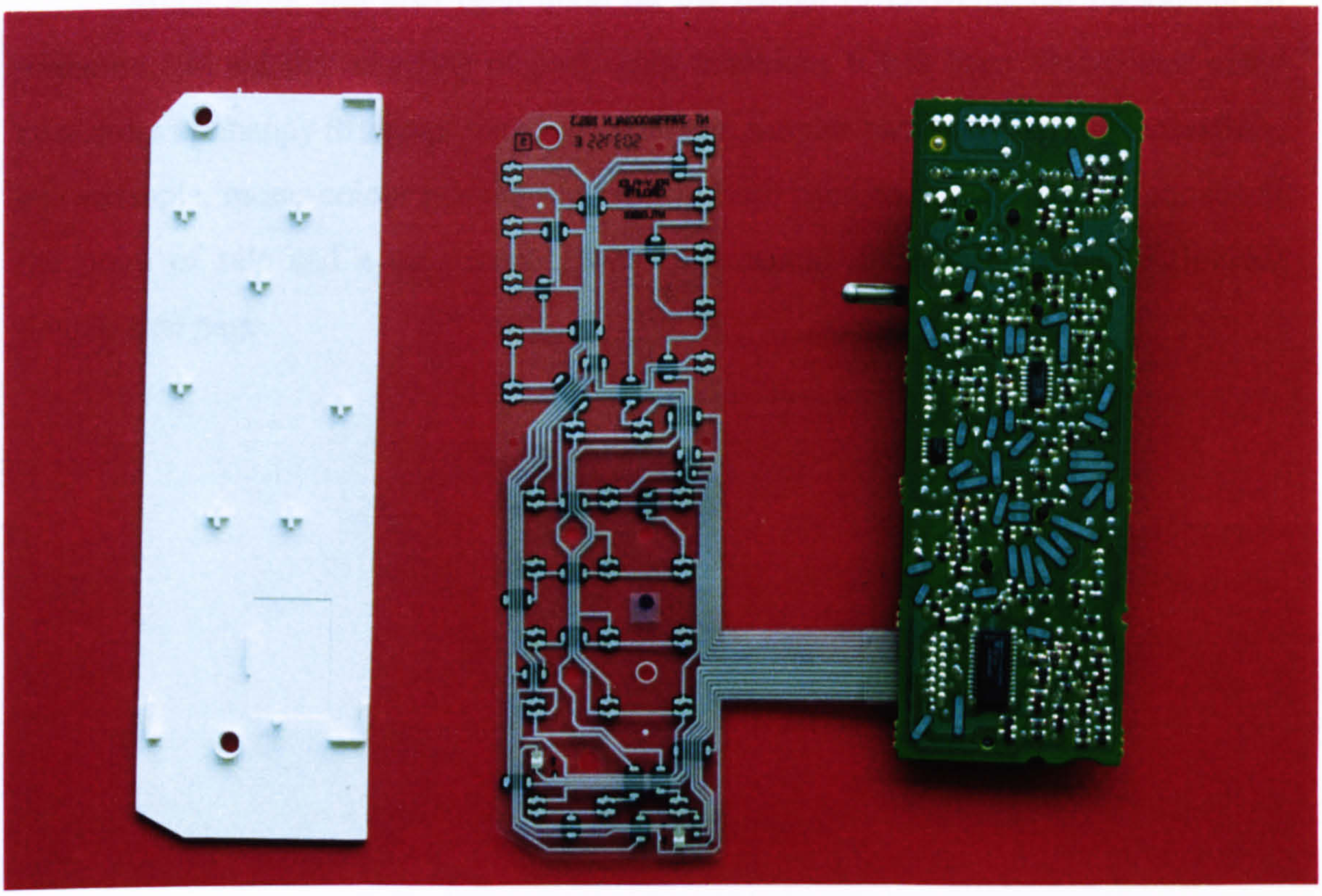

Figure 3.10 Unique construction of a flexible circuit and a separate polymer stiffener for space optimisation to concentrate the high value components in the PCB layout of the Relate 180

Table 3.13 shows the wide variety of printed circuit board technologies applied. It also indicates that some devices contain more than one PCB. Circuit packaging is one of the major design constraints on the telephone product. Inexpensive electronic packaging and printed circuit technologies such as through hole result in large area circuits and hence large external geometry. Techniques such as double sided surface mount and even multichip packaging (as demonstrated by AT&T [Low 95c]) reduce overall size and perhaps reduce the strong coupling between board design and case size for domestic applications but do not usually reduce cost. When telephones are constructed in low cost regions it is not usual to use more advanced electronic packaging technology. The Dialatron telephone includes manually intensive assembly technology but also includes very advanced technologies such as wire bonded bare chip that is likely to be supplied from a more developed economy. This suggests that in future we may have an increasing range of electronic packaging technologies.

Much work has also been done on the design of conventional packaging to minimise and aid the recycling of packaging materials. It has been shown that many customers are happy to accept recycled materials, simpler packaging and fewer leaflets. For example, mono-colour printed boxes have been used to contain the telephones at the point of sale and a user manual was concise and limited to one large (folded) double side page.

Printed circuit board assembly, process conditions										
Telephone model	**Type of board**	**Through-hole technology**	**Mixed technology**	**Surface-mount technology**	**Chip-on-board technology**	**Reflow soldering**	**Wave soldering**	**Manual soldering**	**Keypad contacts**	**Others**
Relate 100	Double-sided populated, single-sided board	-	☑	-	-	☑	☑	-	Carbon screen printed	-
Relate 180	Double-sided populated, single-sided board	☑	☑	☑	-	-	☑	-	Keypad contacts carbon screen printed on attached flexible circuit board	
Relate 300	Double-sided populated, double-sided board	-	☑	-	-	☑	☑	-	Carbon screen printed	-
Duet 200	Double-sided populated, double-sided board	-	☑	-	-	☑	☑	☑	Carbon screen printed	Rigid/ flex connectors
Dialatron Call Timer	Double-sided populated, single-sided board	☑	-	-	-	-	☑	-	-	Rigid/ flex connectors
	Single -sided populated, single-sided board	☑	-	-	-	-	-	☑	Gold plated	Rigid/ flex connectors
	Double-sided populated, double-sided board	☑	-	-	For LCD unit	-	-	☑	Gold plated	Rigid/ flex connectors
Converse 300	Double-sided populated, double-sided board	-	☑	-	-	☑	☑	☑	Gold plated	-
Euroset 802	Single-sided populated, single-sided board	☑	-	-	-	-	☑	-	Carbon screen printed	-
Euroset 812	Double-sided populated, double sided board	☑	☑	-	-	-	☑	-	Carbon screen printed	-

Table 3.13 Comparison of PCB assembly technologies

3.3.3 Design rules for remanufacture and resale

Remanufacturing requires: (i) Product return and checking for damage (ii) Disassembly of specific parts (iii) Sorting of parts according to their recycling requirements (iv) Cleaning and repair (v) Assembly and testing [Clegg 95]. The essential goal in remanufacture is part reuse, which in itself approaches the ultimate form of waste reduction. Though reuse may be identified with products of low manufacturing cost, short innovation cycles and short life spans, this problem is overcome in lease-oriented devices such as telephones where the product is covered by warranty and whose recovered components can be used in remanufacture or repair.

During product manufacture, much of the value is added by the assembly process itself as it constructs a functioning system from its components. However in the course of remanufacture a degree of disassembly is normally required to extract the required components - this represents a loss in the value added as the product is stripped of its materials and loses its functional properties. The difference between remanufacture and reuse is that the latter aims at preserving as much of the product integrity as possible (i.e. all of the value added including that during assembly) this precludes significant disassembly. Ideally, a product should be "reused" in its entirety, alterations should be minimal such as only changing the logo. This will not only be cost effective but will help to ameliorate EOL considerations as well by extending life.

The telephone specific rules developed for remanufacture to date are: to keep the button array ordered on disassembly and to ensure compatibility on remanufacture electronic sub-assemblies need to be clearly marked with the product identity. There is also a need to design a product logo that may be easily replaced by another (see table 3.14).

Design for remanufacture and resale	
20	To ensure compatibility on remanufacture, mark all electronic sub-assemblies with product identity.
21	Keep the numeric button array ordered on disassembly.
22	Design for second market while generating first market product.
23	Logo should be easily removed and replaced by another.

Table 3.14 Telephone specific rules for remanufacture and resale

Through communication with BT, Nortel, Frazier and Mayer Cohen*, it is clear that there is a significant opportunity for volume second marketing of telephone products as the "EOL" products in this particular case are still functional and retain considerable value. Furthermore the infrastructure for resale is yet to reach maturity. However, at present remanufactured products appear to be supplied to less discriminating markets - they are usually downgraded to suit a less sophisticated market place. At present, remanufactured British telephones are mainly sold to second markets mainly in former Russia and the Eastern European bloc. There is also interest in the East African market (to countries with British influence) as well as the rest of the EU. China is not an immediate choice due to market protectionism from the government.

Matching refurbished telephones to the second market telecommunications infrastructure currently requires installation of an additional resistor or capacitor. It also appears that circuitry of older telephones are normally easier to alter (such as changing the dial tone by shorting certain wires, etc.) when compared to newer phones with integrated circuits. However building in consideration for second market such as circuit switching is likely to save money in mass volume remanufacture. Justification of this functionality will require an understanding of the extra cost involved in "waste exports", the associated legislative boundaries and the design features required. However, it is also hoped that future EU harmonisation in telecommunication standards will put an end to the problem of circuit matching within Europe.

*Within the context of this work, BT is a telecommunications service provider, Nortel is a telephone manufacturing company while Frazier and Mayer Cohen are telephone recyclers.

3.3.4 Impact of design for recycling and disassembly on manufacturing costs

As has already been discussed design decisions such as electronic packaging and assembly styles have significant effects on manufacturing costs. The discussions on manufacturing cost impacts of design for disassembly have been primarily carried out with two companies, Nortel (South Wales) and Inventec (Malaysia). Each company is of a different character. Nortel designs and manufactures telephones in South Wales using sophisticated surface mount technology on highly automated lines and has carefully organised cells of people carrying out final assembly - this approach is driven by high local labour costs. Inventec in contrast uses large quantities of less expensive labour both in manual soldering and board assembly. While the Malaysian plant specialises in high volume production (Inventec having four times the production volume of Nortel), the UK factory produces products that are geared towards end-of-life solutions.

It is clear that Nortel have been tackling the issues associated with design for assembly and design for disassembly for sometime - their new design in the Relate 180 fulfilled 16/23 of the design rules developed. While the assessment of the Relate 180 showed it is only marginally behind the German products (which broke the least rules), the Relate 300 and Duet 200 appears to have broken the most rules, as depicted in table 3.15. Discussion showed that Nortel's approach of using a flexible circuit and a separate polymer stiffener (made from recycled material) increased recyclability by reducing board area, concentrating components and increasing unmixed polymer content (see figure 3.10).

	Design Guidelines	Relate 100 (NT)	Relate 300 (NT)	Relate 180 (NT)	Duet 200 (Inventec)	Dialatron (China)	Converse 300 (Inventec)	Euroset 802 (Siemens)	Euroset 812 (Siemens)
1	Reduce total number of screws to secure sub-assemblies (i.e. use snap fits, mould in parts, etc.)	☑	☑		☑	☑	☑	☑	☑
2	Design numeric keypads to fall out on dismantling.	☑	☑						
3	Mount *all* electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible.		☑		☑	☑	☑		☑
4	Avoid using additional (lead/ plasticine) weights in base unit or handset.	☑	☑	☑	☑	☑	☑		
5	Avoid the use of glue either as a encapsulator or fastener. Also avoid using sticky/ adhesive tapes to secure wire, components, etc.				☑	☑	☑		
6	Design removable rubber feet pads from base unit.				☑	☑	☑		
7	Design easily detachable LCD display unit (i.e. use plastic snap-on brackets, adhesive flexible connectors).	NA	☑	NA	☑		☑	NA	
8	Use push-in plugs that are easy to pull out.	☑	☑	☑	☑	☑	☑		
9	Combine separate silicone pads into one.		☑				☑		
10	Use minimum paper labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.	☑	☑		☑	☑	☑		
11	Use detachable wire connections instead of soldered leads.				☑	☑	☑		
12	Design sub-assemblies that have open access for dismantling (i.e. PCB mounting, battery compartments, LCD display unit, etc.)	☑	☑		☑	☑	☑		
13	Use single plastic type throughout (including numeric keypads), preferably in darker colours.	☑	☑		☑	☑	☑		
14	Mould in material identification on plastic body.					☑			
15	Design PCBs that concentrate high value components.	☑	☑	see *	☑	☑	☑	☑	☑
16	Use matt/ textured surface finish - tends to hide minor moulding flaws better than high gloss finish.	☑	☑		☑	☑	☑		

	Design Guidelines	Relate 100 (NT)	Relate 300 (NT)	Relate 180 (NT)	Duet 200 (Inventec)	Dialatron (China)	Converse 300 (Inventec)	Euroset 802 (Siemens)	Euroset 812 (Siemens)
17	Avoid moulding in metal threads/ inserts into plastic body.		☑						
18	Minimise the use of spray painted logos.	☑	☑		☑	☑	☑		
19	Use mono-colour printed box for packaging. Operator's manual should be concise - if possible limit instructions to one large (folded) double sided page.	☑	☑	☑	☑	☑	☑		
20	To ensure compatibility on remanufacture, mark all electronic sub-assemblies with product identity.	☑	☑	☑	☑	☑	☑	☑	☑
21	Keep the numeric button array ordered on disassembly.	☑	☑	☑	☑	☑	☑	☑	☑
22	Design for second market while generating first market product.	☑	☑	☑	☑	☑	☑	☑	☑
23	BT logo should be easily removed and replaced by another.	☑	☑	☑	☑	NA	☑	NA	NA
	Total	15	19	7	19	18	20	5	6

* Relate 180 effectively satisfies this guideline by its use of a flexible sheet backed by a separate recycled polymer stiffener.

Table 3.15 Best practice guidelines broken by various telephone models

These design changes had been made with minimum impact on the cost of the telephone - a cut of 5-10% being achieved. The manufacturing costs (£8.50) of the Nortel phone are dominated by the board assembly cost (around 50%) and by materials (£7.50 of which £2 is polymers) labour is only £1 of these costs. The changes necessary for improved disassembly/ assembly have included the use of higher cost components and connectors - this reflects Siemens experience, the overall reduction in cost has been achieved by light weighting of the case (3 mm to 2.7 mm thick) and by manufacturing cost improvements and the use of cheaper electronic components.

Inventec in contrast identify that changes to the design would involve significant cost - the changes required being extremely significant. There has been historically no need to be attentive to design for assembly because of the labour costs. Also of note is the additional cost envisaged by Inventec for an increased size silicone button mat. This is due to a requirement for new tooling or machines rather than using components used in other phones. Table 3.16 compares the available cost estimates by Inventec against the telephone best practise guidelines. The figures are also displayed alongside estimates for changes in disposal costs by Manchester Metropolitan University (MMU) in earlier collaborative work [BT 95c].

Disassembly rules (Ranked)		Δ Disposal costs (MMU est.)	Inventec manufac-turing cost est.
1	Reduce total number of screws to secure sub-assemblies (i.e. use snap fits, mould in parts, etc.)	-6%	+ 10 to 15%
2	Design numeric keypads to fall out on dismantling.	-24%	
3	Mount *all* electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible.	-14%	
4	Avoid using additional (lead/ plasticine) weights in base unit or handset.	Lead: +5% Others: -5%	
5	Avoid the use of glue either as a encapsulator or fastener. Also avoid using sticky/ adhesive tapes to secure wire, components, etc.	Glue: -7% Per tape: -1%	
6	Design removable rubber feet pads from base unit.	No change	
7	Design easily detachable LCD display unit (i.e. use plastic snap-on brackets, adhesive flexible connectors).		
8	Use push-in plugs that are easy to pull out.	-2%	
9	Combine separate silicone pads into one.	-3% per pad	+ 8 to 10%
10*	Use minimum labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.	-2% per label	
11	Use detachable wire connections instead of soldered leads.	No Change	
12	Design sub-assemblies that have open access for dismantling (i.e. PCB mounting, battery compartments, LCD display unit, etc.)	Varies	+ 10 to 15%

Recycling/ Materials Recovery rules			
13	Use single plastic type throughout (including numeric keypads), preferably in darker colours. Maximise the use of recycled materials whenever possible.	No sorting: -2% No ident.: -5%	
14	Mould in material identification on plastic body.	No Change	
15	Design PCBs that concentrate high value components.	+2% (?)	
16	Use matt/ textured surface finish - tends to hide minor moulding flaws better than high gloss finish.	No Change	
10*	Use minimum paper labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.	-2% per label	
17	Avoid moulding in metal threads/ inserts into plastic body.	25% (revenue increase per part)	
18	Minimise the use of spray painted logos.	No change	
19	Use mono-colour printed box for packaging. Operator's manual should be concise - if possible limit instructions to one large (folded) double sided page.	No change	
Design for remanufacture and resale			
20	To ensure compatibility on remanufacture, mark all electronic sub-assemblies with product identity.		
21	Keep the numeric button array ordered on disassembly.		
22	Design for second market while generating first market product.		
23	BT logo should be easily removed and replaced by another.		

Table 3.16 Inventec/ MMU cost estimates against best practise guidelines

Nortel consider that the manufacturing cost of their telephone is 50p more than Inventec. They consider that this arises from the effect of cheaper labour within the complete supply chain. The potential manufacturing cost effects are presented in a composite table (see table 3.17) featuring generic guidelines developed by MMU and mapped alongside the telephone specific best practise rules developed from this work.

Cost	MMU Compilation	LU Compilation	Rank
	Generic design guidelines	**Telephone specific Best Practise**	
+	Minimise the number of different types of material	Use single plastic type throughout (including numeric kaypads), preferably in darker colours. Maximise the use of recycled materials whenever possible.	
0	Make subassemblies and inseparably connected parts from the same or a compatible material.	Use single plastic type throughout (including numeric kaypads), preferably in darker colours. Maximise the use of recycled materials whenever possible.	
0	Mark all plastic and similar parts for ease of identification.	Mould in material identification on plastic body.	
0	Use materials which can be recycled.		
0	Use recycled materials.		
-	Ensure compatibility of ink where printing is required on plastic parts.	Minimise the use of spray painted logos.	
0	Eliminate incompatible labels on plastic parts.	Use minimum paper labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.	
0	Hazardous parts should be clearly marked and easily removed.		
-	Minimise the number of fasteners.	Reduce total number of screws to secure sub-assemblies (i.e. use snap fits, mould in parts, etc.)	1
0	Minimise the number of fastener removal tools needed.		
0	Fasteners should be easy to remove.	Design numeric keypads to fall out on dismantling.	2
0	Fastening points should be easy to access.		

+	Snap-fits should be obviously located and able to be disassembled using standard tools.	Use push-in plugs that are easy to pull out.	8
+	Try to use fasteners of material compatible with the parts connected.		
0	If two parts cannot be compatible make them easy to separate.	Design removable rubber feet pads from base unit.	6
		Design easily detachable LCD display unit (i.e. use plastic snap-on brackets, adhesive flexible connectors).	7
+	Eliminate adhesives unless compatible with both parts joined.	Avoid the use of glue either as a encapsulator or fastener. Also avoid using sticky/ adhesive tapes to secure wire, components, etc.	5
+	Minimise the number and length of interconnecting wires or cables used.	Mount *all* electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible. * Current BT industrial designs may not support this.	3
0	Connections can be designed to break as an alternative to removing fasteners.		
-	Minimise the number of parts. * Current BT handset weight specifications do not encourage this.	Mount *all* electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible. * Current BT industrial designs may not support this.	3
		Combine separate silicone pads into one.	9
		Avoid using additional (lead/ plasticine) weights in base unit or handset.	4
-	Make designs as modular as possible, with separation of functions.		

+	Locate unrecyclable parts in one area which can be quickly removed and discarded.		
+	Locate parts with the highest value in easily accessible places.	Design PCBs that concentrate high value components.	
0	Design parts for stability during disassembly.		
0	Avoid moulded-in metal inserts or reinforcements in plastic parts.	Avoid moulding in metal threads/ inserts into plastic body.	
0	Access and break points should be made obvious.		
**Potential manufacturing cost effects are represented by (+ increase, 0 no effect, -decrease)			

Table 3.17 Composite MMU/ LU design guideline comparison

Telephone specific guidelines s/n 12, 16, 19-23 below are not mapped onto MMU list:

12	Design sub-assemblies that have open access for dismantling (i.e. PCB mounting, battery compartments, LCD display unit, etc.)
16	Use matt/ textured surface finish - tends to hide minor moulding flaws better than high gloss finish.
19	Use mono-colour printed box for packaging. Operator's manual should be concise - if possible limit instructions to one large (folded) double sided page.
20	To ensure compatibility on remanufacture, mark all electronic sub-assemblies with product identity.
21	Keep the numeric button array ordered on disassembly.
22	Design for second market while generating first market product.
23	BT logo should be easily removed and replaced by another.

It should be observed that the Siemens family of products has a clear family of internal electronics designs that use similar footprints. This is not true in the new Nortel designs (even given the similarity of the exterior of the telephones). This reflects the decoupling of the industrial design and design for manufacture functions and the multiple sourcing of products from vendors that use different internal designs. This adds to the final overall manufacturing cost of the telephone range. This also is likely to support upgrade.

These observations identify that design changes to support EOL aspects have a significant manufacturing cost impact and are likely to add significantly to the cost of the device to the customer. There is little evidence at present that the customer will support a green premium. This highlights that extending the life of existing designs - and their corresponding manufacturing facility - by achieving a second market for the products with a minimum of intervention both is commercially attractive and potentially reduces environmental impact. This work has also appeared in earlier publications by the author [Low 95d, Low 96a].

3.3.5 Conclusions

The above case study has identified a set of design features for design for disassembly, recycling, remanufacture/ resale particularly focused on telephones as the most representative telecommunications customer premises equipment. It has highlighted that though some design features are desirable for EOL impact, these were often constrained by design specifications.

The largest constraints on manufacturing cost reduction and the implementation of changes driven by environmental considerations were found to be the external styling of the telephone in combination with some of the constraints within the BT specification. The layout of the printed circuit board, the most expensive item of the design, is particularly affected by the external design of the telephone and the space available within the device.

It has also indicated that a closer collaboration between industrial design and design for manufacture could allow improvements in EOL impact by allowing better use of PCB real-estate available area and height. Consideration of the reuse of components and subassemblies and the impact of design changes on manufacturing cost highlights that a single lifetime EOL design approach loses much of the value added to a material during its manufacture. This again highlights reuse - without refurbishing - as both the most cost effective and least damaging approach from overall

EOL considerations. There are perceived to be significant market opportunities associated with selling remanufactured products in emerging markets in Eastern Europe and the Pacific Rim whose indigenous manufacturing capacity does not match their market size.

3.4 Application of best practise rules to a further telecommunications device, the pager

The above telephone case studies represent a class of mature telecommunications products which possesses electronics technology of a moderate sophistication. The bulk of the high value components are contained within the printed circuit board and dominates the manufacturing cost at roughly 50%. This is in contrast with the pager device, a class of relatively new portable wireless telecommunications product that requires PCB design of high complexity as well as more demanding manufacturing processes. Table 3.18 compares the differences between the telephone and the pager (the "Cello" model from Motorola is used in this study). Although similar electrical/ electronic items are used in both products (as indicated by s/n 1-6), they support somewhat different functionalities.

The pager example also provides an interesting contrast with a desktop telephone in terms of both product/ market maturity as well as technology complexity. The pager is particularly selected as an exemplar product in this instance to test the applicability of the best practise telephone rules developed; however, the end of life management of the pager will not be dealt with in this study.

s/n	Electrical/ electronic item	Desktop telephone (Relate 300)	Pager ("Cello" from Motorola)
1	Tone caller/ buzzer	Yes.	Yes.
2	PCB (s)	Yes.	Yes.
3	Batteries	Yes. For telephone number storage only. Non-essential.	Yes. Essential for message retrieval.
4	LCD screen	Yes. For programming/ displaying phone numbers. Still functional without.	Yes. To display caller messages, etc. Essential.
5	ROM/ RAM	Yes. For telephone number storage.	Yes. For storage of functions such as caller messages, time, etc.
6	LED light	Yes. As a visual indicator.	Yes. Used for dim lighting conditions.
7	Vibrator unit	NA	Yes. Used as an alternative alert mode for incoming messages.
8	Radio wave receiver	NA	Yes. Essential for message receiver operation
9	Wire cords & socket connectors	Yes.	NA
10	Handset	Yes.	NA
11	Volume control	Yes.	NA
12	External Microphone	Yes.	NA

Table 3.18 Comparison of functional properties of electrical/ electronic items in a desktop telephone and a pager

3.4.1 Assessment of telephone best practise rules on the pager

A recapitulation of the best practise rules are listed and the assessment of the rules to the pager are remarked on the following line.

Rule 1: Reduce total number of screws to secure sub-assemblies (i.e. use snap fits, mould in parts, etc.)

Though only 2 screws are used, special keys are required to dismantle the pager. Product contents fall apart relatively easily since it has a shallow assembly depth.

Rule 2: Design numeric keypads to fall out on dismantling.

Key pads are push fit. Falls out easily.

Rule 3: Mount all electrical/ electronic components onto PCB. Optimise component layout on board to eliminate wire connections if possible.

Rule violated. Metal inserts are also found in the plastic battery chassis because of scale and strength issues.

Rule 4: Avoid using additional (lead/ plasticine) weights in base unit or handset.

Not applicable.

Rule 5: Avoid the use of glue either as a encapsulator or fastener. Also avoid using sticky/ adhesive tapes to secure wire, components, etc.

Glue/ tape used on PCB but has no contact with plastic shell.

Rule 6: Design removable rubber feet pads from base unit.

Not applicable.

Rule 7: Design easily detachable LCD display unit (i.e. use plastic snap-on brackets, adhesive flexible connectors).

Use of flexible connector for LCD similar to the German Euroset phones.

Rule 8: Use push-in plugs that are easy to pull out.

Not applicable.

Rule 9: Combine separate silicone pads into one.

Not applicable. Only one silicone pad being used.

Rule 10: Use minimum paper labels (mono-colour print) or employ alternative labelling techniques (i.e. mould in labels). Reduce process "quality control" stickers.

Rule violated. Lacquered paper labels used.

Rule 11: Use detachable wire connections instead of soldered leads.

Vibrator unit is the only component that uses soldered leads. It may be too small to use detachable leads.

Rule 12: Design sub-assemblies that have open access for dismantling (i.e. PCB mounting, battery compartments, LCD display unit, etc.)

Product has shallow disassembly depth. Use of pin-slot connector to interconnect and secure the two PCBs does not encourage quick disassembly, however it holds the sub-assemblies firmly in place.

Rule 13: Use single plastic type throughout (including numeric keypads), preferably in darker colours.

Rule violated.

Rule 14: Mould in material identification on plastic body.

Material identification found on both plastic body and external pocket housing.

Rule 15: Design PCBs that concentrate high value components.

Not applicable. The circuit board has a scattering of high value components but there are within very close proximity to each other. This is due to the space constraints within the palm-sized housing.

Rule 16: Use matt/ textured surface finish - tends to hide minor moulding flaws better than high gloss finish.

Feature employed on both body housing and external pocket housing.

Rule 17: Avoid moulding in metal threads/ inserts into plastic body.

Rule violated. Metal threads and inserts found in both plastic body housing and external pocket housing. Glue is also used to hold LCD window and foam paddings to the main housing.

Rule 18: Minimise the use of spray painted logos.

Not applicable.

Rule 19: Use mono-colour printed box for packaging. Operator's manual should be concise - if possible limit instructions to one large (folded) double sided page.

Rule violated. Coloured boxes used for packaging.

Rule 20: To ensure compatibility on remanufacture, mark all electronic sub-assemblies with product identity.

Rule violated.

Rule 21: Keep the numeric button array ordered on disassembly.

Not applicable.

Rule 22: Design for second market while generating first market product.

Rule violated. Design for second market requires building in compatibilities for frequency reception. Second market infrastructure will also have to support textual broadcast facilities.

Rule 23: Company logo should be easily removed and replaced by another.

Rule violated.

3.4.2 Observations and remarks

The pager comprises four major subassemblies: main housing, printed circuit board, button key pad and the external pocket housing (see figure 3.11). Owing to the shallow depth of disassembly, the major components of the pager are separated quite easily after removing the 2 screws in the battery compartment. The ease of part separation is however contrasted by the more difficult materials separation within the subassembly. This is represented by the violation of best practise rules 10, 13, 17 - the use of glue, foam paddings, lacquered adhesive papers and metal inserts on the plastic chassis has severely discouraged the ease of recycling of the ABS housing. It is possible to reuse some components in the PCB assembly such as the vibrator unit and the buzzer, however the permanent attachment of these devices to the board indicate there is no intention of reusing them. This suggest that the end-of-life management of the pager may not be fully mapped out at the design stages. The assessment of the telephone guidelines to the pager indicate that 7 of 23 best practise rules are fulfilled, 9 are violated and 7 are non-applicable. While this result appears to indicate that the pager may not have been optimised for end of life recovery, a majority of the telephone rules (about 70%) are still generic to the pager, the remaining rules will however require more product specific considerations.

Compactness and portability is prerequisite to pager design - there is an overall reduction in the size of the product which is complimented by an increase in functionality over time. The comparison of the "Cello" pager with an older "Multitone" pager demonstrated this case in point. This down sizing effect with "packing more into lesser space" is made possible by radical changes in PCB technology - the printed circuit board is noted to be the highest value added assembly in the pager.

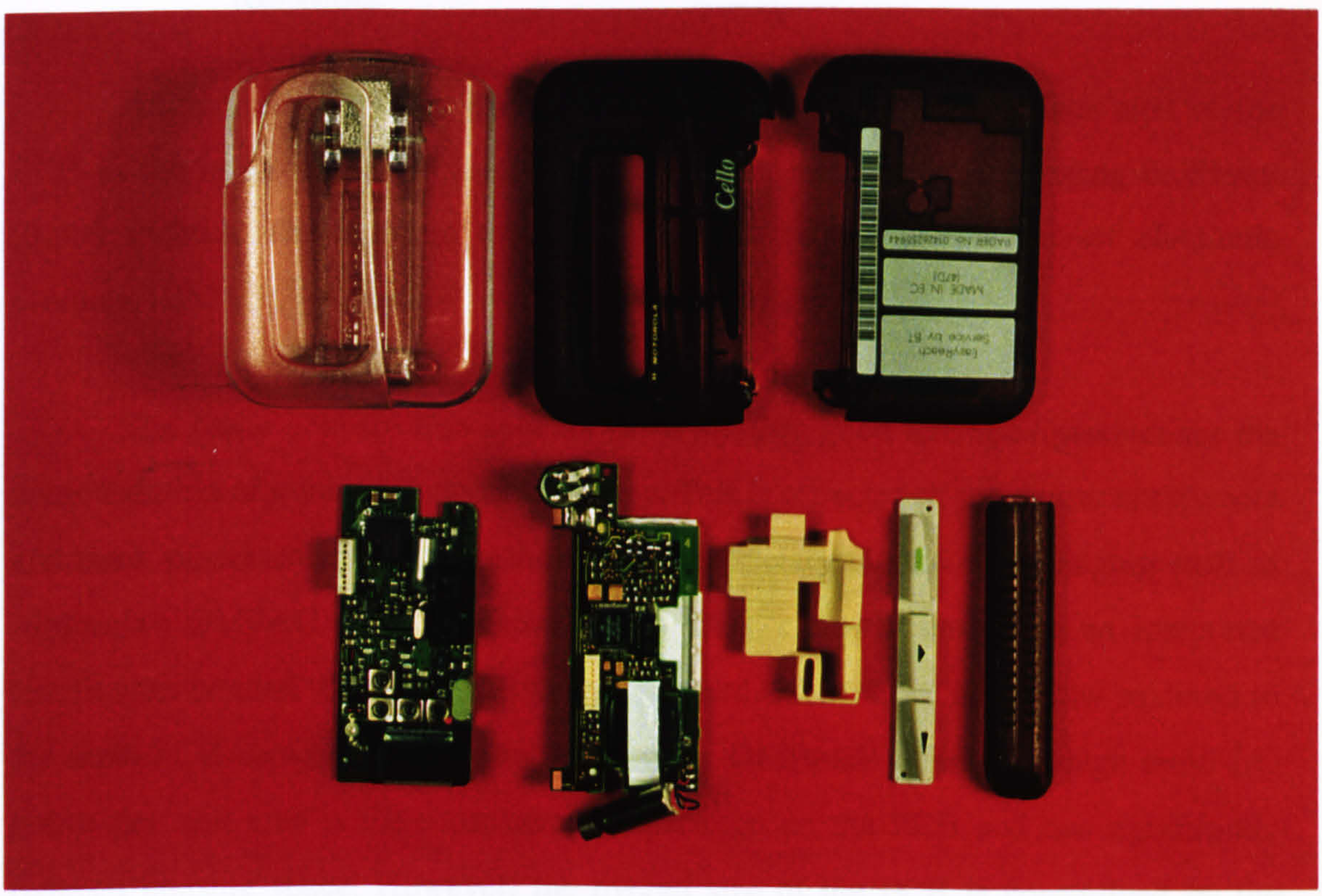

Figure 3.11 Various subassemblies of the Motorola "Cello" pager

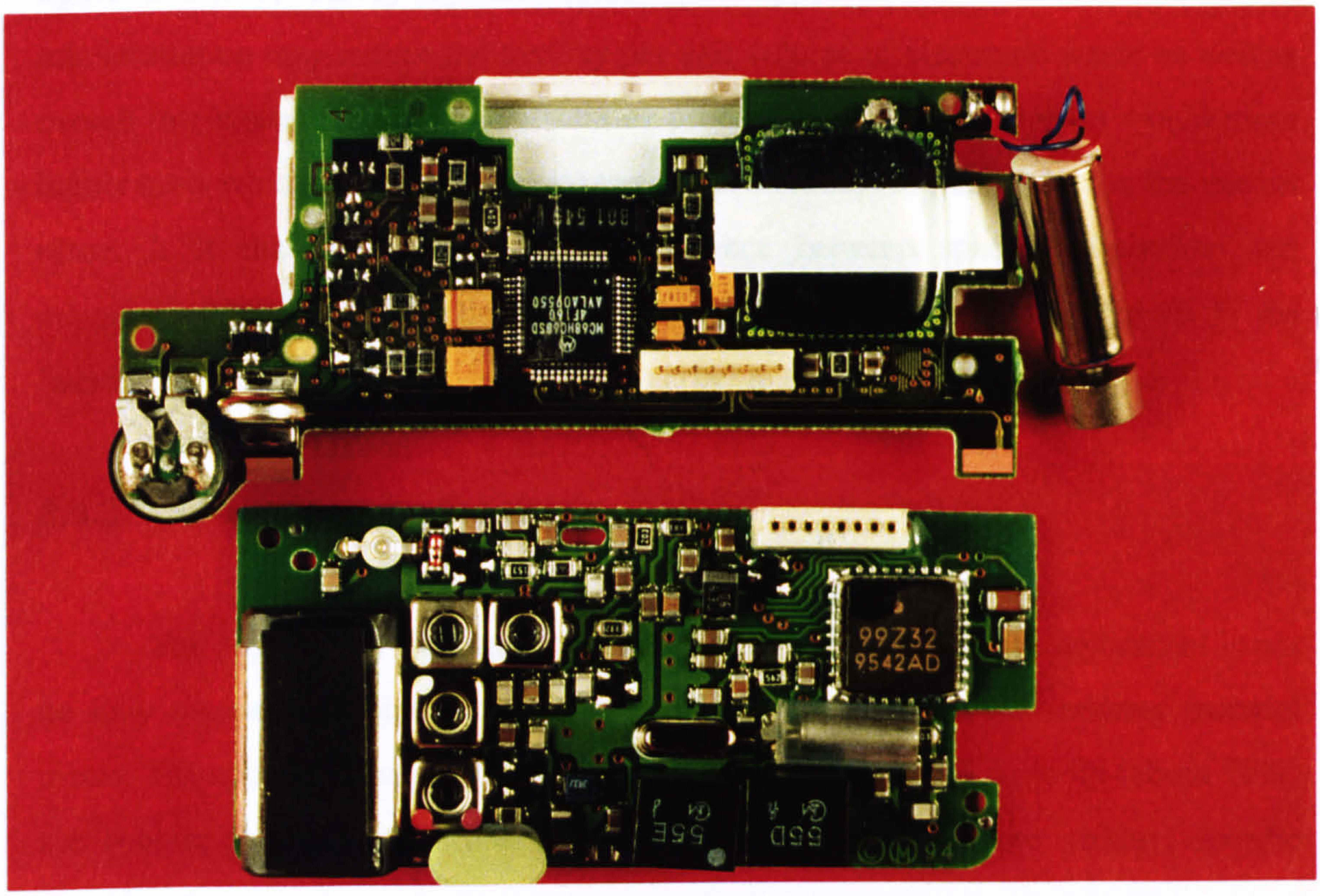

Figure 3.12 PCB layout of the pager depicting a mixture of both fine and coarse pitch components

An approximate calculation revealed a 20% reduction in surface area of the PCB in the latest design with one of the smallest track width measuring 0.081mm (0.003 inches). This appears to be in line with most state-of- the-art electronic products [IPC 95].

The pager concept also appears to be another good exemplar product for the demonstration of miniaturisation technology. This is reflected in the denser component and track placements as well as the use of proprietary electronic packaging such as Motorola's OMPAC (over moulded plastic array carrier) comprising an integrated circuit wire-bonded to a rigid PCB daughter board, which is in turn reflow soldered to the main PCB using ball grid array techniques. OMPAC's offering of high multi I/O points per unit area is the most complex package on the PCB and has significantly reduced housing space. However, the overall size of the PCB is constrained by the bulk of some of the populated devices such as the capacitors, buzzer, etc. which does not appear to match the finer pitches state-of the-art chips are able to sustain (see figure 3.12). A survey by the author (see appendix A) indicated that whilst miniaturisation may reduce the toxicity per unit volume of electronic waste as well as overall raw materials in the manufacturing process, the tighter tolerances would mean higher costs which in turn may reduce the competitiveness of the product in the market place. It is thus sensible to find the balance between space optimisation and miniaturisation; this is best depicted by the PCB design which expanded to fit the internal housing in both the pager and the earlier telephone studies.

3.4.3 Conclusions for the pager

The pager study indicates that end-of-life management of the equipment is not be fully mapped out at the design stages, in particular those that address material mixes. The application of the telephone design rules show that a majority (about 70%) are generic to the pager while the remaining rules require more product specific considerations.

3.5 Conclusions for the chapter

The current approach to product design is being increasingly driven by environmental concerns which requires consideration from a life cycle perspective. This draws together DFA and DFDA methodologies at the conceptual stage. Although taken independently, they have very different financial goals, finding an optimum manufacturing/ end-of-life strategy often reflect a compromise likely to be dictated by the type of product manufactured. Telephone handsets considered in the case studies represent a mature volume product with a well established reprocessing infrastructure. The hastening of environmental legislation added further interest to optimising the product for end of life recovery. This however may not be the case for a less mature electronic product such as the personal stereo or the personal computer where the rate of change of technology makes end-of-life reprocessing technically more challenging and perhaps financially not viable. More often, the lack of financial incentives in such cases may overshadow environmental responsibilities, one of the likely solutions to this problem could perhaps be achieved through heavy legislative penalties.

The telephone design rules for disassembly, recycling, remanufacturing/ resale identified in the study highlighted that the major constraints were within the design specifications. These design specifications in combination with the external styling of the telephone contributed to the largest constraints on the manufacturing cost reduction. This also reflect the current "arms length" relationship between BT, the telephone stylist and the manufacturer which significantly reduce the opportunities for improved environmental impact and reduced manufacturing costs that would be possible in a more integrated environment. The impact of design changes on manufacturing cost also highlights reuse without refurbishing as both the most cost effective and least damaging approach from overall end of life considerations.

The pager study indicates that whilst a majority (about 70%) of the telephone design rules are generic to the pager the remaining rules require more product specific considerations. As an example of miniaturisation technology, the pager may also reduce the toxicity per unit volume of electronic waste as well as overall raw materials in the manufacturing process; however, tighter tolerances often mean a price increase and may thus reduce the overall market place competitiveness of the product. The balance between pricing, space optimisation and miniaturisation is best depicted by the PCB which expanded to fit the internal housing in both the pager and the earlier telephone studies.

CHAPTER 4

Economic modelling for the end-of-life management of electronic products

4.0 Introduction

This chapter focuses on the links between the commercial and technological issues that have to be faced in the end-of-life management of electronic products. Telephones have again been used as exemplar products in this study. The various EOL stages considered are: Resale, Remanufacturing, Recycling, Upgrade and Disposal. Given the lack of data on both environmental and commercial aspects, the simplest predictive forecasting model is a linear one and this gives a sensible starting point that will allow the development of more complex models later in this chapter. The immediate section will review related work in this area and define the scope of various EOL options. This is followed by outlining the various overheads required in processing each particular option as well as its design implications. The models are then derived and matched to current commercial data for a number of telephone models. The chapter closes by discussing a number of issues that arise from the modelling work.

4.1 Review of related work

Using mathematical modelling with cost as a common platform in the comparative study of green design is relatively new. The closest work is that of Matthews et al. [Matthews 95], Shu et al. [Shu 95], Willems et al. [Willems 95], Dowie et al.[Dowie 95a] and Stuart [Stuart 96].

The Carnegie Mellon University approach in [Matthews 95] uses two components of product costs (Ci): manufacturing (Mi) and turnaround (Ti) costs and is modelled after a remanufacturable product i.e. a toner cartridge. The model is able to simulate life time cost comparisons and product recovery costs for a number of given life cycles. The fraction of components to be reused (k) is first estimated (i.e. the toner and reservoir seal in the case of the toner cartridge) and is expressed as a fraction of the manufacturing cost as in equation 4.0:

$$Ci = (1\text{-}k)Mi + Ti \qquad (4.0)$$

The model is later extended to include sensitivity analysis of any extra costs for quality improvement (see equation 4.1) as well as taking into account price setting situations to meet break even costs for a given scenario (see equation 4.2) e.g. when not all products are returned.

$$C^* = C + \varepsilon\,(n - nk + k + \delta - n\delta) - [\delta\,(n\text{-}1)]\,M_1 \qquad (4.1)$$

where C* is the cost of the product with quality improvement and δ represent the increase in the recyclability factor as a result of initially building in an additional ε value such as investing more on its initial manufacture to facilitate future recycling. The values n, C and M_1 represent correspondingly the number of times the product is sold, the life time cost and the initial manufacturing cost.

$$D_i = \sum_{1}^{i} C_k - ip \qquad (4.2)$$

where D represents the initial deposit with life time cost i and selling price p

The approach appears to be comprehensive and attractive at first glance but has major drawbacks for generic use: resale prices do not vary with the number of uses; it assumes cost of disposal is equal to the value of recycled materials and further assumes products are sold and returned in a short period such that the interest rate (or opportunity cost of the capital) can be treated as zero. However, the biggest advantage is the ability to iterate product recovery cost estimations for a given number of life cycles which, unfortunately, appears to be largely attributable to the mathematical manipulations that tended to over-simplify the overall pricing scenario in remanufacturing. It however provides an interesting starting point.

The research framework in [Shu 95] centres around the selection of fastening and joining methods for the remanufacturing of toner cartridges. This product specific approach requires vigorous application of both work-time study data and probabilistic determination of part failures such as rivet and fastener damage. The various cost components are calculated and summed to give the total cost of remanufacture (see equation 4.3). The approach also appears to have little genericity compared to the work in [Matthews 95] though both models are based on the same product as follows:

$$C_{rm} = (T_d + T_a)L + P_f C_f + (P_{pd} + P_f P_{pe} - P_{pd} P_f P_{pe})C_p \qquad (4.3)$$

where

C_{rm} = Remanufacture cost
T_d = Disassembly time
T_a = Assembly time
L = Labour rate
P_f = Probability of fastener failure in disassembly and assembly
C_f = Cost of fastener failure
P_{pd} = Probability of part failure in disassembly and assembly
P_{pe} = Probability of part failure in fastening-method extraction
C_p = Cost of part failure

Willems et al. [Willems 95] proposed an Environmental Design Cost (EDC) model which attempts to capture the optimal EOL processing strategy costs by considering an array of factors such as factory cost price, life expectancy and product return percentage for each different product. The output of the EDC provides designers cost calculations for elements such as changes in production costs when the product is modified and the present value of future EOL processing cost (see equation 4.4) as follows:

$$PVFC = FC / (1+k)^t * \text{collection } \% \qquad (4.4)$$

where

PVFC = present value of future end of life processing costs
FC = future end of life processing costs

k = cost of capital of the company
t = life time of the product

Of particular interest is the method for calculating the present value of future EOL processing cost. The proposed formula however appears to be a close mapping of the economics formula for calculating present value cost with compound interest i.e. $S/(1+i)^n$. However, there are some terms within the model that are ill defined (i.e. return percentage and cost of capital). At present the equation represents only a conceptual approach, the model would require further refinements including a clear definition of terms in order to forecast any useful data.

The Manchester Metropolitan University (MMU) approach in [Dowie 95a] involves identifying and classifying operations in disassembly and establishing a set of synthetic times which correspond to the disassembly operations. Labour rates and related overheads are assigned to each dismantling procedure, the total time taken and cost incurred are then estimated; revenue costs associated with materials recovery are also included in the final cost tabulation. This solely addresses estimation of the cost of operation.

Stuart [Stuart 96] proposed an EPPACE (Emerging Product, Process and Consideration of Environment) model that formulate a quantitative approach to evaluate the economic, environmental and quality differences among product and process alternatives. A mixed integer programming model was developed to capture process activities such as assembly, rework, disassembly repair and refurbishment. The model also serves as a decision tool from the manufacturer's viewpoint to analyse the impact of pollution minimisation over time, waste attributed to poor quality, future legislation and product take back.

4.2 Linear models

Building a coherent framework that links commercial and technological issues in EOL management will be challenging especially given the need to ascertain several vital variables with little historical data and are difficult to predict, such as the volume of returned products and quantity of products to be sold in a second market. Clegg in collaboration with Uzsoy [Clegg 95] recognises the need for a linear model (one which contains variables related by a linear relationship where the value of the constant is important) as it simplifies the complex economics and logistics issues involved in the various EOL routes taken. Even then, his model dealt with the interactions of different cost components and production system characteristics in remanufacturing and recycling, these alone involve no fewer than 25 parameters, 14 decision variables and 10 constraints. The materials flow in the Clegg/ Uzsoy model is represented in figure 4.0.

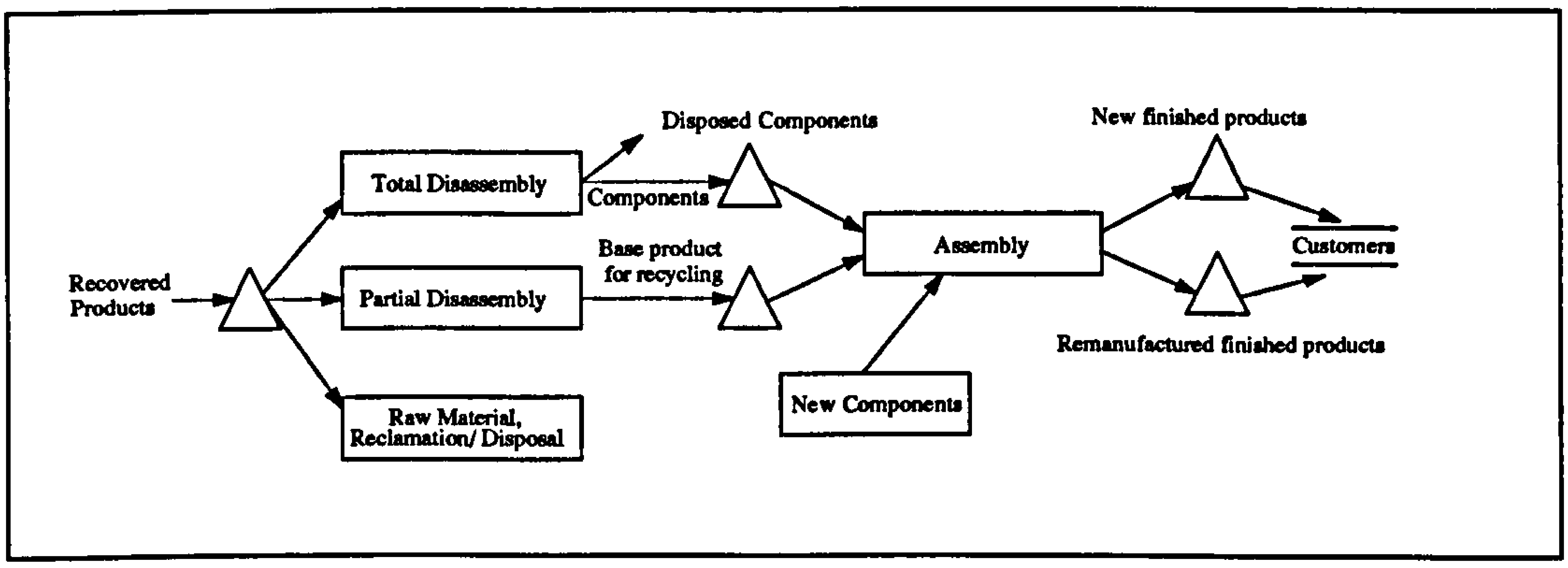

Figure 4.0 Material flow in a company with remanufacturing capability

Though the scenario is basic, the control volume is affected by the rate of returned products, the reprocessing routes including the inventory levels of various intermediate items as well as the demand of reprocessed items by the market. The accuracy of the model is highly dependent on the detailed data structure required for individual stages. This approach appears to be cumbersome and not yet practical as a design tool to quickly access the trade offs being different EOL strategies. Understanding the complex drivers involved in each of the EOL option is however necessary before a further abstraction can be made to present them in a digestible easy-to-use format. This will call for a different approach and further simplification to the equations concerned without having to make too much compromise on its reliability.

4.3 Modelling approaches to end-of-life models

A number of approaches to modelling the problem can be considered. One of the formats that is used by designers, which is apparently captured by software writers is the ability to manipulate variables to see the outcome of "what-if" scenarios. Forecasting will be determined by the relevant equations - the choice of variables used as well as the graphical representations will need to be determined and could be established by one of the following approaches:

4.3.1 Deviation score from an "ideal" design

The design is scored from its deviation from the "ideal" design. This approach will have to initially focus on defining an "ideal" product and thereafter devise a scoring system to assign an overall score to each design route for each EOL option. This approach is somewhat similar to a hybrid of Boothroyd-Dewhurst DFA design assessment technique [Boothroyd 83] and Allenby's matrix for DFE analysis [Allenby 92]. Cost calculations may be absent in this approach which also implies that knowledge of detailed cost models is removed or may not be absolutely necessary provided an appropriate metric is used. The main advantage is that it enables the overall approach to be more generic and quickly adaptable over a range of other electronic products.

4.3.2 Cost based design approach

The second approach is to examine the product design using cost calculations as a common platform. Cost trade offs for different EOL options are projected for each design route and the best design could then be chosen. As opposed to (i), this will require a good understanding of the various costing aspects - factors that are less understood such as packaging, testing, logistical and related costs for refurbishing a product. Second market sizes for a resale product must also be further researched. The use of a cost based metric also allows some translation between sub problems facing different issues.

Many forecasting elements will be involved in this approach. Since there exists only few reliable data at present, output results could be equally unreliable and misleading. This approach may be less generic as separate case studies are required to establish the economic model for each product type and range. However, as economic drivers largely determine the success or failure of a product, a monetary platform model presents a more realistic feel to the designer for a given budget constraint (a common problem for industrial designers).

4.3.3 Nomogram approach

The third approach is to capture the design trade-offs based on series of tables/ graphs which gives the designer an "instant cost calibration" of the particular design route. This is likened to a tool kit (nomogram) for the travelling salesman as he reads off the graph in an instant the cost for a particular repayment period when requested to do so by the client. Like the cost based design approach in the previous section, this approach will require heavy forecasting and experience similar problems. In particular it requires plotting many variables and does not include or present any depth of understanding of the problem. Furthermore, the designer is limited only to the variables presented on the "calibrated" graphs and does not have the options to explore related factors

Of the three approaches described above, the cost based approach in section 4.3.2 is preferred as it gives a wider scope for an overall integration of commercial and financial decisions within a technological framework. Given the lack of data on both environmental and commercial aspects, the simplest predictive forecasting model is a linear one and this gives a sensible starting point that will allow the development of more complex models later in the chapter. A family of models will be outlined below pertaining to the five choices of EOL management. To better illustrate the derivation of the models, the desktop telephone Relate 100 is used as an exemplar product. The model requires the definitions which follow† as presented within the context of the modelling problem.

4.4 Resale

Resale is defined as an operation whereby the existing product is recovered and sold, with minimum intervention, to another customer requiring similar product function. This may be in the same geographical location or may be in another more distant second market.

The various overheads are:

(i) Logistics (product recovery and transport to second market)

- Product recovery could be through: agent, collection centre, return envelope and other schemes
- Transport to second market takes into account overheads to all modes of transport. (Truck loads, ship containers, etc.)

(ii) Inspection and cleaning (up to or close to first market standard)

(iii) Testing (to ensure that the product is working, may include at this stage minor adjustments of electronics in product to match infrastructure of second market i.e. power supply settings)

(iv) Packaging (for transport to second market or may be done at second market)

(v) Others* (printing of labels, new logo, instruction booklets, etc.)

4.4.1 Design Implications for Resale

Products for resale should be clearly identified at the start of first life including building in variants for the second market. Maximising durability is also important,

†These definitions were developed in collaboration with the industrial partner BT for this work.

*These are dictated by more minor issues such as cultural preference of colours, language displays on liquid crystal displays, etc. Such overheads are likely to be small and would usually constitute changes to the repackaging and overall aesthetics of the equipment.

considerations are given to factors like cosmetic features, functional reliability, "look" or aesthetics as well as the cleanability of the product. The logo should be also easy to change and the instructions/ markings etc. must be readable in the second market. Other factors to be considered include: building in compatible function for target market, fitting the product into standard packaging as well as ensuring the availability of spares and consumables. and are complimentary to the design rules developed in section 3.3.3.

4.5 Remanufacture

The product is recovered and either restored to its original condition (both function and cosmetics) or its function is modified. This includes the reuse of components and materials.

The various overheads are:

(i) Logistics (include product recovery and delivery)
- Product recovery as in resale
- Delivery costs will likely to be based on the number of truck load constructed from a consolidated waste stream

(ii) Disassembly and sorting (cost = time taken x labour rates)

(iii) Inspection and cleaning

(iv) Additional refurbishing (if required, such as polishing or part replacements)

(v) Re-assembly (if required, of subassemblies that were previously cleaned)

(vi) Testing (for operation readiness)

(vii) Packaging (normally not as elaborate as for resale items)

4.5.1 Design Implications for Remanufacture

Products designed for remanufacture should embody the following criteria: cleanable to first market standards which also means that parts that are to be replaced must be easily accessed and identified. Modules should also have durable high value subassemblies with the necessary built in test points. They should also be designed with easily replaceable wear parts where improvement of such wear parts cannot be cost justified. The design implications for remanufacture supports the design rules developed for remanufacture and resale in section 3.3.3.

4.6 Upgrade

The existing product is given improved functionality on the customer premises.

4.6.1 Design Implications for Upgrade

Products that are designed to be upgradeable should be modular and have a durable skeleton and core technology. It is also desirable to have standardised interfaces to encourage customer-friendly upgrades. The external design should also be stabilised, thereby reducing the number of customers likely to replace their product in order to follow fashion or other trends.

4.7 Recycling

The product is disassembled to recover the materials and perhaps components but normally loosing its function as a system.

The various overheads are:

(i) Logistics (product recovery and delivery)
   - Product recovery as in resale
   - Delivery of product will be based on the number of truck loads

(ii) Cleaning (components that can be reused)

(iii) Disassembly and sorting components and materials for reuse and recycling

(iv) Recycling (cost will include mixing with virgin materials if required)

(v) Packaging

(vi) Disposal of remaining scrap from (iii)

4.7.1 Design Implications for Recycling

Products designed for material recycling should minimise materials mixtures to enable quick disassembly into its constituent parts. It is important also to mark the materials used so they can be easily identified. Collection costs can also be minimised if the volume and mass of the design is reduced accordingly - this will however be moderated by safety and other constraints. The design implications for recycling are complimentary to the design rules developed for recycling in section 3.3.2.

4.8 Scrap

Product and or its elements go to landfill or incineration.

The various overheads are:

(i) Logistics (product recovery and delivery to landfill or incineration)

(ii) Disassembly and sorting (normally part of an earlier process to separate the value added material from scrap items)

(iii) Disposal landfill costs and toxicity surcharge

4.8.1 Remarks and design implications for Scrap

Scrapping the entire product is often seen as the last option in EOL management however, it occurs in some proportion in almost all the options described above. Ultimately, all products will have to be disposed when all forms of life extensions are exhausted. Scrap should be "designed" to have minimal value and maximum density if possible. From the environmental point of view, materials must be selected such that the risks of toxic contamination are reduced to a minimum. Designers should avail themselves of the relevant standards for certain toxic substances. If toxic materials are to be used, they should then be designed for easy separation.

A summary of the data checklist required for each individual EOL route is represented in table 4.0 below. Additional reprocessing considerations are shown in brackets.

Cost data required	End-of-life routes				
	Resale	Remanufacture	Upgrade	Recycling	Scrap
Logistics	X	X		X	X
Inspection and cleaning	X	X		X	
Disassembly and sorting		X		X	X
Additional refurbishing (i.e. polishing, part replacement)		(X)			
Re-assembly		(X)			
Testing	X	X			
Packaging	X	X		X	
Recycling				X	
New module		(X)	X		
Disposal (landfill, etc.)		X		X	X
Others (Labels, booklets, etc.)	X				

Table 4.0 Checklist of data required for each EOL route

4.9 Derivation of model 1

The first model assumes that the overheads considered in the various EOL operations be expressed as a coefficient of the manufacturing cost of the product. This sets a linear relationship between the two variables. The models also capture the profit being generated by the particular EOL option as well as the total profit earned combining both first and second life options.

4.9.1 Derivation of Resale model

The equation for resale overheads may be expressed as a fraction of the manufacturing cost (M):

$$\text{Resale overheads} = \alpha M \qquad (4.5)$$

The coefficient α captures the overheads arising from (i) to (v) in section 4.4. If we consider the profit to be generated from the initial manufacturing process to be:

$$\Pi_{New} = [\text{Selling price } (P_N) - \text{Overheads of new products } (X_N)] \times \text{Quantity of new products}(Q_N) \text{ at time t}$$

$$= (P_{Nt} - X_{Nt})Q_{Nt}$$

and the profit from the resale process may be expressed as:

$$\Pi_{Resale} = [\text{Selling price } (P_R) - \text{Overheads of resale products } (X_R)] \times \text{Quantity of resale products } (Q_R) \text{ after time i}$$

$$= (P_{Rt+i} - X_{Rt+i})Q_{Rt+i}$$

From (4.5),

$$X_{Rt+i} = (\alpha M)_{t+i}$$

Therefore the total profit is:

$$\Pi_{Total\ profit} = \Pi_{New} + \Pi_{Resale}$$

$$= (P_{Nt} - X_{Nt})Q_{Nt} + (P_{Rt+i} - [\alpha M]_{t+i})Q_{Rt+i} \qquad (4.6)$$

4.9.1.1 Remarks for Resale model 1

The term $(P_{Nt} - X_{Nt})Q_{Nt}$ for new products are normally well established and are based on reliable research statistics for a target segment of the market. However, price setting for the resale products after period ***i*** is much less understood hence the term $(P_{Rt+i} - [\alpha M]_{t+i})Q_{Rt+i}$ becomes more unpredictable. The linear approach to estimating the resale overheads may also appear to put too much burden on the single coefficient, α. However, this engineering approximation represents a generous trade off between ease of calculation and the lack of data and is in contrast to the approach undertaken by Clegg/ Uzsoy [Clegg 95].

4.9.2 Derivation of Remanufacture model

The equation for remanufacture overheads may be expressed as a fraction of the manufacturing cost (M):

$$\text{Remanufacture overheads} = \beta M + S$$

The coefficient β captures the total overheads described from (i) to (vii) in section 4.5 expressing it as a fraction of the manufacturing cost M for every item or module considered for remanufacture. The remaining components that are scrapped and must be disposed of are represented by the cost function S given by:

$$S = \text{Weight per item [landfill cost per unit weight + toxicity landfill surcharge]}$$

Total profit may be expressed similar to (4.6) as:

$$\Pi_{\text{Total profit}} = \Pi_{\text{New}} + \Pi_{\text{Remanufacture}}$$

$$= (P_{Nt} - X_{Nt})Q_{Nt} + (P_{Rt+i} - [\beta M + S]_{t+i})Q_{Rt+i}$$

4.9.2.1 Remarks for remanufacture model 1

When calculating the remanufacturing overheads, the following constraints are not considered: (i) Inventory holding costs for returned and remanufactured products (ii) capacity constraints for the remanufacturing process and waste disposal. Again, major uncertainties arise from estimating the market demand for the remanufactured goods at time *t+i*. However, the Mayer Cohen experience with remanufactured telephone sets provided a starting point to ascertain the variables within the model and this is demonstrated in the worked example using the Relate 100 telephone set later in the chapter.

4.9.3 Derivation of Upgrade model

Since upgrading provides the added functionality at a later date (t+i), the purchased modules are treated as new products with overheads typical of conventional manufacturing processes. The overheads for the new products (v) can be expressed as a fraction (γ) of the manufacturing cost (M) of the functional core:

$$\text{Upgrade overheads} = \sum_{v=1}^{n} \gamma_v M$$

It is also worth noting that it is possible that $\gamma > 1$ for upgrades with complex functionalities. In any case, the total profit generated may be expressed as follows:

$$\Pi_{\text{Total profit}} = \Pi_{\text{New}} + \Pi_{\text{Upgrades}}$$

$$= (P_{Nt} - X_{Nt})Q_{Nt} + (P_{v,t+i} - \gamma_{v,t+i}M)Q_{v,t+i} \qquad (4.7)$$

4.9.3.1 Remarks for Upgrade model 1

The upgrade concept of products is not new and has been marginally successful with a handful of electronic products, such as computers. The market in this aspect has been well researched and factors that will affect the sale of the products ($P_{v,t+i}Q_{v,t+i}$ term in equation 4.7) are largely dependent on rate of change in technology development, maturity of product in the market place, price competition of new products as well as cultural shopping patterns in society. A recent upgradeability study of 3 consumer electronic products with considerations given to the above factors indicated that while the PC is ideally suited for upgrading, both TV and telephone products are much less likely candidates for upgrading [Bayley 95].

4.9.4 Derivation of Recycling model

The associated overheads for recycling (i) to (vi) in section 4.7 may be expressed linearly with (i), (ii), (iii) and (v) written as fraction μ of the manufacturing cost (M). While (iv) may be calculated by summing all the different materials (P) to be recycled by multiplying their weight (W) with the unit cost (U). Item (vi) are remaining scrapped components to be disposed and are represented by the cost function S:

$$S = \text{Weight per item [landfill cost per unit weight + toxicity landfill surcharge]}$$

Therefore,

$$\text{Recycling overheads} = \mu M + \sum_{p=1}^{n} W_p U_p + S$$

If we consider the market price, P ,of the recycled materials in time t+i to be (P-U) and that for reused components to be r, the total profit generated is represented by:

$$\Pi_{\text{Total profit}} = \Pi_{\text{New}} + \Pi_{\text{Recycled materials}} + \Pi_{\text{Reused components}}$$

$$= (P_{Nt} - X_{Nt})Q_{Nt} + [\sum_{p=1}^{n} W_p (P-U)_{p,t+i} + \sum_{r=1}^{n} (WU)_{r,t+i} - \mu_{t+i} M - S_{t+i}]$$

4.9.4.1 Remarks for Recycling model 1

One of the major uncertainties of the model lies in the estimation of material prices in the future. Given an accurate forecast, it would have to be translated into present value for future material prices. This approach is similar to the one proposed by Willems et al. [Willems 95].

4.9.5 Derivation of the Scrap model

The logistics and Disassembly costs can be represented as a fraction,τ of the manufacturing cost (M). Disposal cost is estimated by multiplying the weight (W) by the unit weight cost (Y) and the toxicity surcharge (J) for every item:

$$\text{Scrap overheads} = \tau M + \sum_{j=1}^{n} W_j(Y_j + J_j)$$

A summary of the equations derived for each model is shown in table 4.1 below and an earlier publication by the author [Low 96b].

End of Life Options	ΠNew	ΠOption	ΠProfit = ΠNew+ ΠOption
Resale	$(P_{Nt} - X_{Nt})Q_{Nt}$	$(P_{Rt+i} - [\alpha M]_{t+i})Q_{Rt+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + (P_{Rt+i} - [\alpha M]_{t+i})Q_{Rt+i}$
Remanufacture	$(P_{Nt} - X_{Nt})Q_{Nt}$	$(P_{Rt+i} - [\beta M + S]_{t+i})Q_{Rt+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + (P_{Rt+i} - [\beta M + S]_{t+i})Q_{Rt+i}$
Upgrade	$(P_{Nt} - X_{Nt})Q_{Nt}$	$(P_{v,t+i} - \gamma_{v,t+i}M)Q_{v,t+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + (P_{v,t+i} - \gamma_{v,t+i}M)Q_{v,t+i}$
• Recycle	$(P_{Nt} - X_{Nt})Q_{Nt}$	$\sum_{p=1}^{n} W_p(P-U)_{p,t+i} + \sum_{r=1}^{n}(WU)_{r,t+i} - \mu_{t+i}M - S_{t+i}]$	$(P_{Nt} - X_{Nt})Q_{Nt} + \sum_{p=1}^{n} W_p(P-U)_{p,t+i} + \sum_{r=1}^{n}(WU)_{r,t+i} - \mu_{t+i}M - S_{t+i}]$
Scrap		$\tau M + \sum_{j=1}^{n} W_j(Y_j + J_j)$	

Table 4.1 Model 1 linear equations for each EOL route

4.10 The use of manufacturing cost as a basis for cost calibration

An important assumption implicit in the models is that they are applicable to fairly mature products in the current context - telephone handsets. Figure 4.1 depicts the generic relationship of manufacturing costs to market pricing where the latter is a function of many complex parameters such as brand premium, market loyalty, etc. Market pricing is much more difficult to quantify than parameters related to manufacturing overheads. However, the result of competitive pricing for mature products pushes the pricing line downwards with time. Market pricing for such mature products is much closer to manufacturing costs when compared to a new product. Since telephones are well placed within this mature time frame, the end-of-life models may arguably be justified using manufacturing costs as a basis for economic calibration although this assumption may not hold true for a less mature product.

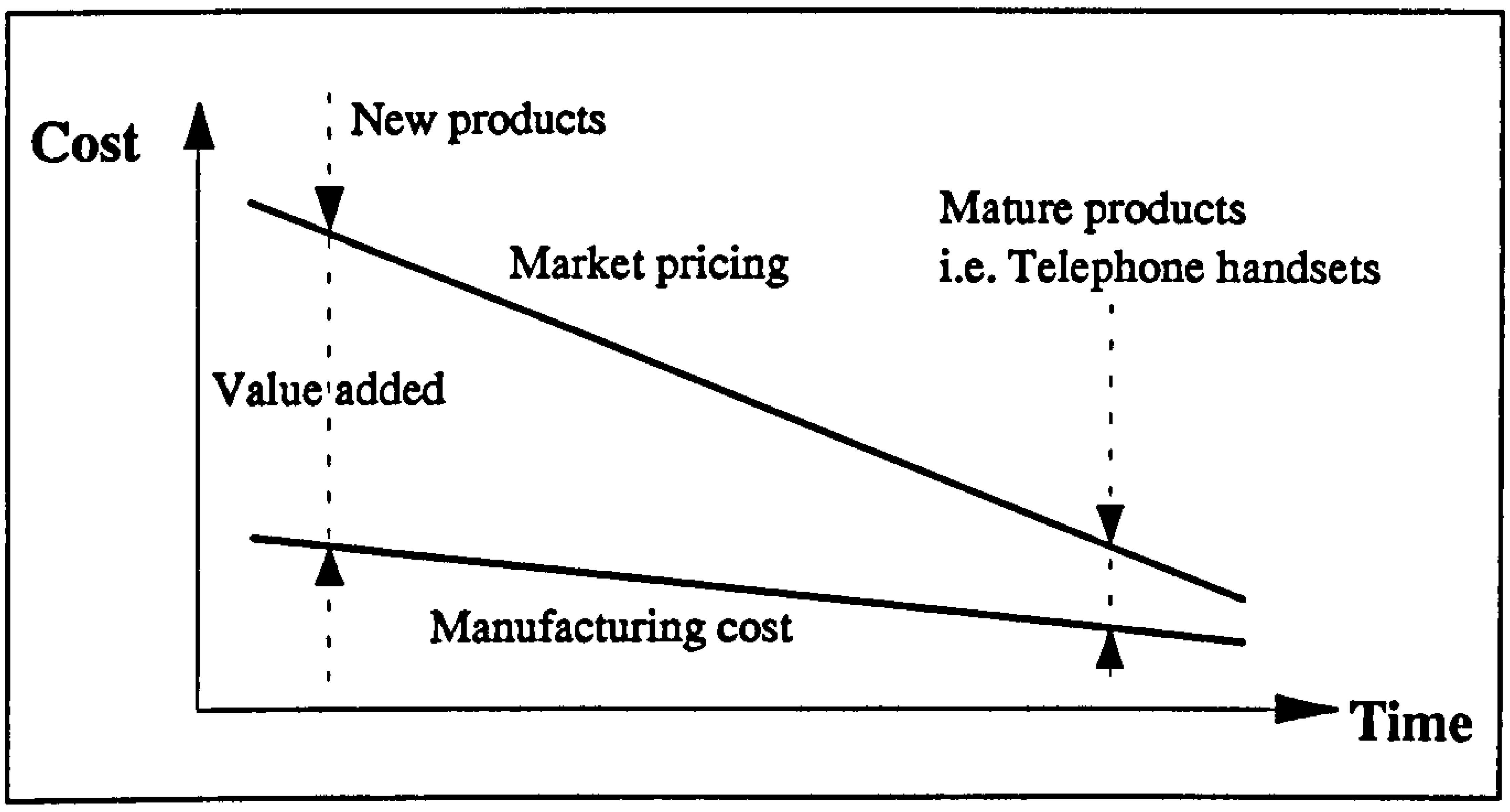

Figure 4.1 Generic relationship of market pricing and manufacturing cost with time

4.11 Description of end-of-life reprocessing operation and simulation of model 1

A typical EOL processing operation will try to maximise the gain from a single product line by combination of several life extension routes instead of performing single re-processing tasks.

The case of the desktop telephone is considered here†. The used product arrives in either jiffy bags or driven in truck loads from collection centres. The phones are sorted according to their models and certain makes are selected for remanufacturing while others will be recovered mainly for the ABS plastic. The phones designated for materials recycling will undergo a manual disassembly procedure to strip all the electronics from the plastic chassis. Some electrical components such as the transducer will be recovered for further reuse while printed circuit boards will be shredded for disposal. The plastic chassis undergo an automated plastic recycling operation which involves crushing the feedstock, melting and purifying through a floatation or filtration process which may at this stage include the addition of virgin plastic. Dye is added and the final plastic reshaped and purity adjusted according to customer requirements. The recycled ABS plastic is then delivered to the customer.

†This particular processing route is an adaptation from the actual operation at Mayer Cohen, a telephone recycler of British Telecom.

The telephones that are designated for remanufacturing will also undergo disassembly to strip off the electronics from the plastic body. In this particular instance, only the plastic chassis will be remanufactured. The numeric buttons are washed and the body panels polished (to remove the logo) and finally both panel and button sub-assemblies are re-assembled to be transported to a second market for reuse.

In the above example, several life extension routes are evident: reuse, remanufacture and recycling. Though the routes taken are not particularly complex, there are instances of overhead duplications when the routes are taken independently, such as collection costs and scrap costs. Care should be taken while calculating these overheads.

Initial EOL cost simulations were performed using the Relate 100 as an exemplar product. The data used were adapted from those collected for an earlier study by Mclaren [Mclaren 96] carried out for BT. The particular routes considered were: Resale, Recycling and Remanufacturing. The Upgrading route is not available for the Relate 100 due to design limitations and hence simulations were not performed. Calculations are based on total 500 000 manufactured units of which 375 000 are returned for reprocessing. The simulation results are presented in table 4.2, figure 4.2 offers similar results in graphical form. Detailed calculations for each option within the models are contained in appendix C.

End-of-life Operation	**Revenue from 500 000 new units [£ in millions] (A)**	**Revenue from reprocessing 375 000 units [£ in millions] (B)**	**Net revenue [£ in millions] (A+B)**
Resale	9.22	3.42	12.64
Recycling	9.22	-1.17	8.05
Remanufacturing	9.22	3.35	12.57
Scrap	9.22	-1.13	8.09

Table 4.2 Summary of simulation results for Relate 100

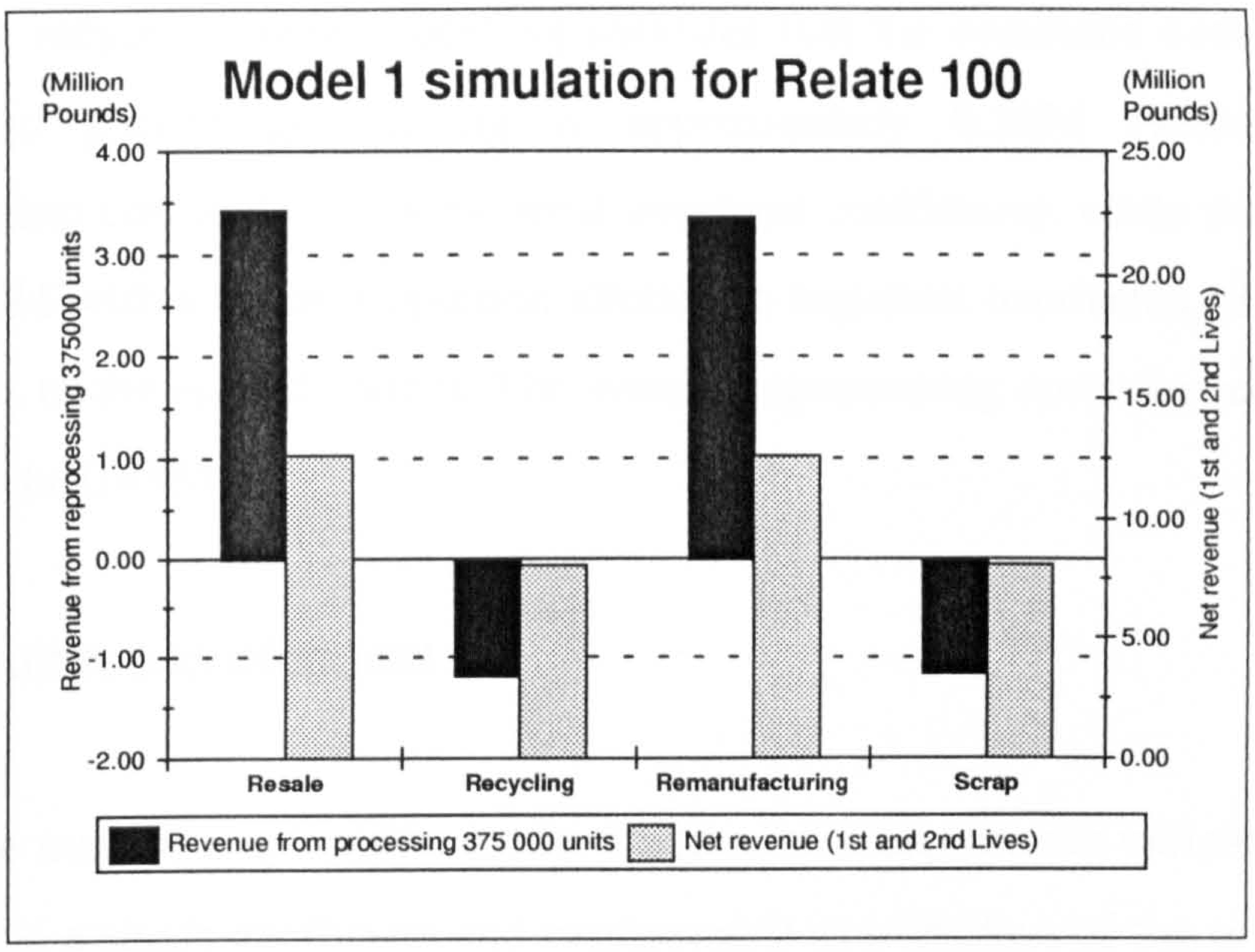

Figure 4.2 Summary of model 1 simulation results for Relate 100

4.11.1 Comparison of options

Initial modelling indicates that both resale and remanufacturing operations appear to be profitable while recycling is not (see table 4.2). The profitability of these two options are accounted for by selling the reprocessed product at significantly higher prices, these amount to about half the retail price of a new product. Details of prices and computation for model 1 are given in appendix C. Recycling on the other hand is non-profitable due to significantly higher logistical overheads compared to the actual reprocessing operations. It becomes apparent that the high takeback costs are alone responsible for the negative revenue.

The simulation results in table 4.2 also highlighted that scrapping the product (i.e. the most environmentally unfriendly option) is marginally less expensive compared to the recycling operation. In the case of the Relate 100, this is due to the assumption that the feedstock to landfill is free from toxic or other substances which could otherwise have required further reprocessing and hence an additional surcharge for special disposal procedures may have been incurred.

For recycling, initial modelling indicates that the combined costs of takeback/ disassembly/ packaging/ cleaning is approximately 0.28M (where M is the manufacturing cost and 0.28 is the total overhead coefficient), while that for resale is about 0.47M with a major proportion allotted to logistical overheads such as shipping of products to the second market. The average reprocessing costs for remanufacturing is found to be 0.49M.

4.11.2 Limitations of model 1

The method employed in model 1 attempts to capture the various reprocessing overheads in a single coefficient and expressing it as a fraction of the original product manufacturing cost. The manufacturing cost is selected as a measuring index as it enables realistic and meaningful comparisons of economic trade offs. However, one major limitation is that it does not distinguish between high and low value added products, this could lead to an over-conservative estimate of the overheads if the problem is not considered in perspective. This limitation is best illustrated by an example.

Example

Consider a resale operation of a simple desktop phone (low added value) with a manufacturing cost M of £12. Take the overall overheads incurred to be 0.45M with a = 0.45 which is a constant variable for resale. Hence,

$$\text{Resale overheads} = aM \qquad \text{(A)}$$
$$= 0.45 * 12$$
$$= £5.40$$

This overhead is in accordance with current reprocessing costs for a simple desktop model and may be accepted as a reasonable projection.

Now consider a resale operation for a multi-function telephone (high value added) with a manufacturing cost M of £30 and a = 0.45. Hence, from equation A,

$$\text{Resale overheads} = 0.45*30$$
$$= £13.50$$

This overhead projection appears to be too high, even for a multi-function phone. One reason is that the model assumes reprocessing costs increases linearly with product complexity. This is not entirely true. In the case of resale, logistical cost is likely to vary with the distance to the second market but is also likely to be a constant value for different types of desktop telephones to the same destination since logistical costs are related to the weight and volume of a product and are independent of its functionality. Reprocessing costs for resale, which normally involve simple testing, inspection and packaging are also fairly independent of the complexity of the product. Thus using manufacturing cost alone (which bears a high correlation to the value added of a product) is not an entirely appropriate measure of EOL reprocessing costs. The over conservative estimate of the required overheads appears to be the major limitation of model 1 and is reflected in the initial simulation for recycling and remanufacturing options in table 4.3. Overheads for the Relate 100 model (a low value added product) are compared with that of the Converse 300 model (a high value added product). The actual estimate of overheads is listed alongside to indicate the extent of deviation. The inflated estimates are highlighted in the shaded boxes. The derivation of actual estimate is shown in Appendix C.

EOL reprocessing options	Relate 100	Converse 300
Recycling overheads (model 1 estimate)	£3.268	£8.404
Recycling overheads (Actual estimate)	£3.268	£3.326
Remanufacturing overheads (model 1 estimate)	£5.606	£14.4
Remanufacturing overheads (Actual estimate)	£5.606	£9.191

Table 4.3 Results of recycling and remanufacturing overhead simulations using model 1 (against actual estimates) for Relate 100 and Converse 300

Model 1 needs improving to distinguish between high and low value added products - part of the goal is also to correct the over projection of the reprocessing overheads. A second model is therefore derived in the following section.

4.12 Derivation of model 2

The conventional manufacturing "cost-plus" model may be expressed as [Product cost] = [Materials costs] + [Manufacturing costs]. In electronic products, the bulk of the value added is encapsulated within the PCB assembly. This may be expressed as [Board] = [Devices] + [Assembly*]. A break down cost model of a handheld telephone shown by Waegner et al. [Waegner 96] suggests that about 3/4 of its cost is dominated by materials whilst the remaining 1/4 are associated with manufacturing overheads. A detailed breakdown of the relative costs are shown in figure 4.3.

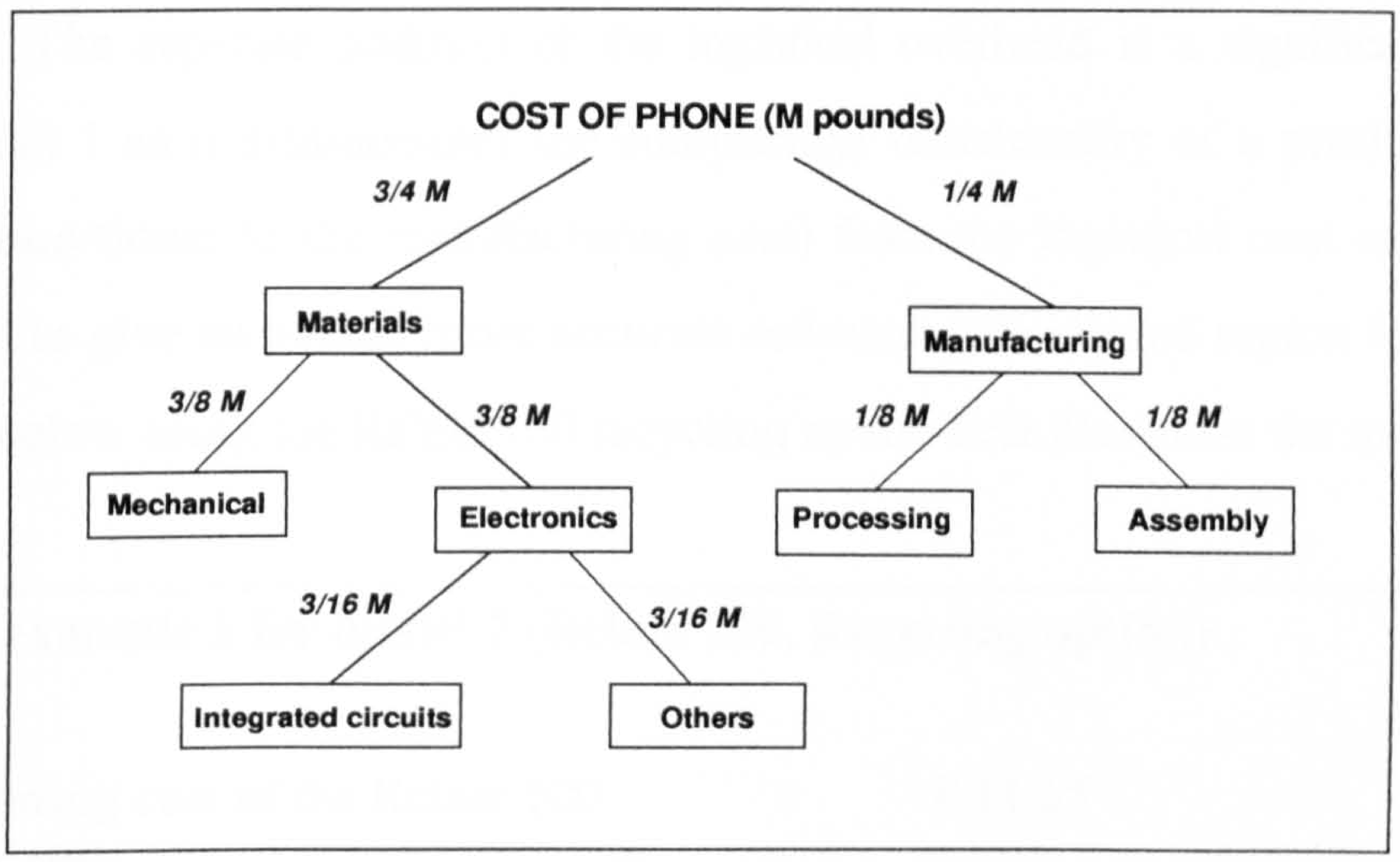

Figure 4.3 Breakdown of the various cost components of a handheld telephone

Of particular relevance of this model to the EOL economic model is the assembly cost, which amounts to about 1/8th the cost of the product. Since most EOL reprocessing involves "demanufacturing" or a partial reversal of the assembly process, Waegner's "1/8 assembly cost" estimate gives a reasonable assumption to the combined costs associated with disassembly, sorting, cleaning etc. within the context of EOL telephone reprocessing. Table 4.4 gives the various types of reprocessing operations that this estimation accounts for. The relative costs of each operation are in turn expressed as ratios for overhead calculation depending on the type of reprocessing operation undertaken. However, implicit to this approach is the assumption that

*The assembly method of PCB is influenced by design factors.

disassembly time is approximately equal to the assembly time or otherwise, disassembly being the complete reverse of the assembly process.

Operation	Disassembly & sorting	Inspection and Cleaning	Packaging and labels, etc.	Reassembly	Testing
Cost (£)	0.087#	0.167*	0.08#	0.087*	0.02*
Relative ratios	0.197	0.380	0.181	0.197	0.045

\# From actual data   * Assumed data

Table 4.4 Price and cost ratios of reprocessing operations based on the Relate 100

Model 2 assumes the overheads such as logistical take back and transportation to the second market are added separately since they are regarded as independent variables. The separate addition of the logistical overhead is a significant departure from model 1 as it disassociates the complexity/ functionality of a product (which is highly proportional to the manufacturing cost) from the logistical cost elements. This has found to give an overall more accurate estimate. The shaded region in the worked example below using the Relate 100 recycling option best illustrates the methodology.

Worked example 1 for model 2 (Relate 100, Recycling option)

Manufacturing cost of the Relate 100 = £ 11.55
Takeback cost = £ 3
Type of reprocessing operation required: Disassembly, Cleaning and Packaging
Cost ratio for disassembly and sorting = 0.197
Cost ratio for cleaning = 0.380
Cost ratio for packaging = 0.181
Total = 0.758
Cost of operation = 0.758 x (1/8) x £ 11.55
= £ 1.09
Cost of takeback + disassembly +cleaning + packaging
= £ 4.098
Cost of disposal/ landfill = £ 0.0039 (129g @ £30 per ton)
Total overhead = £ 4.098

Revenue from sale of ABS = £ 0.0846 (423g @ £200 per ton)
Revenue from sale of PCB = £ 0.000756 (63g @ £12 per ton)
Revenue from sale handset of microphone = £ 0.004
Revenue from sale of phone cord connectors = £0.04 (4@ 1p each)
Revenue from sale of handset speaker = £0.004
Revenue from sale of mixed plastic keys = £0.004

Total revenue	=	£ 0.1374
Net revenue per phone	=	£ 0.1374 - £ 4.098
	=	- £ 3.961

While recycling and resale options for model 2 are calculated as shown in the above worked example, a slight variation is taken in the approach to the calculation of remanufacturing overheads. This is due to the need to take into account faulty parts that require replacement. It is assumed that if the cost to replace all faulty parts were to exceed a pre-determined amount, the product will be scraped as it becomes too expensive to remanufacture. The maximum cost to be incurred for part replacements is adapted from Waegner's model in figure 4.3 as follows - the parts within the phone amount to 3/8th the price of a phone costing M pounds to manufacture or (3/8)M. The average cost for part replacement per phone is assumed to be half of (3/8)M or (3/16)M. This figure is added onto the (1/8)M cost estimate associated with disassembly, sorting, cleaning etc. The combined cost ratios for remanufacturing is the summation of (1/8)M and (3/16)M which gives (5/16)M or 0.3125M. The methodology (in the shaded region) is illustrated below in a second worked example using the Euroset 812.

Worked example 2 for model 2 (Euroset 812 , Remanufacturing option)

Manufacturing cost of phone, M	=	£30
Takeback cost	=	£3
Type of reprocessing operation required:		Disassembly, Cleaning, Reassembly, Testing and Packaging
Cost ratio for disassembly and sorting	=	0.197
Cost ratio for cleaning	=	0.380
Cost ratio for reassembly	=	0.197
Cost ratio for testing	=	0.045
Cost ratio for packaging	=	0.181
Total	=	1
Associated cost ratio of reprocessing	=	0.125
Associated cost ratio for part replacements (assume ave cost)	=	0.1875 or (3/16)
Total	=	0.3125
Cost of operation	=	1 x 0.3125 x £30
	=	£9.375

Total overheads including takeback	=	£12.375
Selling price of remanufactured phone	=	£39
Average revenue per phone	=	£39 - £12.375
	=	£26.625

4.12.1 Simulation results for model 2

Simulations for model 2 were performed for the Relate 100, Converse 300 and Euroset 812 telephone models. The results for the resale, recycling and remanufacturing options are summarised in tables 4.5 to 4.7 and are compared with that obtained in the actual estimate. Details of calculations are found in appendix C.

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Actual estimate of overheads (£)	Net revenue per phone using model 2 (£)
Resale	5.429	5.370	4.767	9.18
Recycling	3.268	4.098	3.268	-3.961
Remanufacturing	5.606	6.609	5.606	7.941

Table 4.5 Comparison of simulation results of model 1 and model 2 for Relate 100

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Actual estimate of overheads (£)	Net revenue per phone using model 2 (£)
Resale	14.100	6.770	4.767	29.230
Recycling	8.404	5.846	3.326	-5.692
Remanufacturing	14.700	12.375	9.191	23.625

Table 4.6 Comparison of simulation results of model 1 and model 2 for Converse 300

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Actual estimate of overheads (£)	Net revenue per phone using model 2 (£)
Resale	14.100	6.770	4.683	32.238
Recycling	8.401	5.671	3.237	-5.580
Remanufacturing	14.700	12.375	9.012	26.625

Table 4.7 Comparison of simulation results of model 1 and model 2 for Euroset 812

The overall simulation results of model 2 indicate that resale and remanufacturing are again the only profitable options since the net revenue for recycling appears to be in the red. It is also observed that model 2 outputs are now closer to the actual estimates when compared to model 1. This indicate that the assumption to exclude takeback/ logistical costs from the manufacturing cost coefficient appears to be a reasonable one and has narrowed the marginal errors, particularly in the resale options. However in the case of remanufacturing there still exists a significant error margin and this prompts further investigation into the initial assumptions. It was earlier mentioned that the results for model 2 were derived based on the "1/8 manufacturing cost estimate" which presumed that disassembly times are equal to assembly times. This also implies that labour costs for dismantling a product and assembling one are similar. The validity of this assumption is examined in the following section to further develop assumptions to be included in the third model.

4.13 Derivation of model 3

The cost model by Waegner et al. was adapted for use in model 2 in the previous section. The model derivation has implicitly assumed the end-of-life dismantling and sorting to be the reverse of the assembly process. However, this is not entirely true in practice because an optimal disassembly path is usually implemented rather than adopting a complete disassembly procedure. Moreover, expensive manual labour is likely to be employed in all dismantling processes as opposed to the use of highly automated processes in modern assembly lines.

Subsequent study and comparison of the various overheads (excluding logistical and disposal costs) has shown that values in model 2 were about 8 times greater then the actual estimate for recycling (see table 4.8), 1.5 times greater for remanufacturing (see table 4.9) and about 8 times greater for resale (see table 4.10). The observations from tables 4.8 to 4.10 indicate that costs associated with EOL disassembly is significantly smaller than the assembly processes. This follows that disassembly labour costs are not likely to be equal to assembly costs and could be expressed as:

Disassembly cost = k*Assembly cost = k*(Employment cost + overheads)

where k is an empirical constant and k < 1/2

The Euroset 812 model was chosen to be modelled in addition to the Relate 100 and the Converse 300 as it represented the best in class designed telephone that was available for study and is anticipated to provide the necessary illustrative contrasts between the products.

	Overheads for Recycling (excluding takeback/ logistics and disposal costs) (£)		
	Relate 100	Converse 300	Euroset 812
Model 2 estimate	1.098	2.84	2.84
Actual estimate	0.268	0.326	0.237
Error factor	4.10	8.71	11.98
Average error factor	8.26 (or multiply by 0.12)		

Table 4.8 Error deviation for recycling overheads for model 2

	Overheads for Remanufacturing (excluding takeback/ logistics and disposal costs) (£)		
	Relate 100	Converse 300	Euroset 812
Model 2 estimate	3.609	9.375	9.375
Actual estimate	2.606	6.191	6.012
Error factor	1.38	1.51	1.56
Average error factor	1.48 (or multiply by 0.67)		

Table 4.9 Error deviation for remanufacturing overheads for model 2

	Overheads for Resale (excluding takeback/ logistics and disposal costs) (£)		
	Relate 100	Converse 300	Euroset 812
Model 2 estimate	0.87	2.27	2.27
Actual estimate	0.267	0.267	0.183
Error factor	3.26	8.50	12.40
Average error factor	8.05 (or multiply by 0.12)		

Table 4.10 Error deviation for resale overheads for model 2

Model 3 is derived based on the understanding that disassembly times may not accurately approximate assembly times and that the time-to-labour overheads for these operations are unlikely to be interchangeable. However, it is reasonable to assume that EOL economic models require a foundation of a calibrated financial platform and that first life models are arguably able to provide such an environment, it is thus assumed that the use of a correction factor to bridge the two models (both first life and EOL) may justify the approach adopted in model 3, given current data resources. The factor correction to estimate the overheads for the various EOL options, excluding both logistical and disposal costs are: 8.26 for recycling, 1.48 for remanufacturing and 8.05 for resale in the current context. These figures represent the average error deviation of model 2 results from actual estimates for the three telephone models (see tables 4.8 to 4.10). The new revenue equations for model 3 are presented below for resale, recycling and remanufacturing options. The definition of symbols are coherent and similar to those presented in model 1 (see table 4.1).

4.13.1 Resale revenue equation for model 3

Resale Overheads per unit	=	$\alpha M + T$	where M is Manufacturing cost and T is Logistical costs
And α	=	(ΣCost ratios of reprocessing operations)*(1/8)* (Factor correction for resale)	
	=	(0.606)(0.125)(0.12)	
	=	9.09×10^{-3}	
Therefore,			
Resale Overheads	=	$(9.09 \times 10^{-3})M + T$	
Selling price	=	P	
Quantity	=	Q	
Revenue from Resale	=	(Sale price-overheads)*Quantity sold	
	=	$\{P - [(9.09 \times 10^{-3})M + T]\}*Q$	
	or	$\{P - [\alpha M + T]\}*Q$	

4.13.2 Recycling revenue equation for model 3

Recycling Overheads per unit	=	$\mu M + T + S$	where M is Manufacturing cost and T is Logistical costs and S is disposal cost

Where μ = (ΣCost ratios of reprocessing operations)*(1/8)* (Factor correction for recycling)
= (0.758)(0.125)(0.12)
= 11.37×10^{-3}

Where S = Weight per item (landfill cost per unit weight + toxicity landfill surcharge)

Revenue from recycled materials and reused components

$$= \sum_{p=1}^{N} W_p P_p \quad \text{where W is weight per unit}$$

P is revenue price per unit

Therefore,

Revenue from Recycling

= (Revenue from recycling materials - Overheads)* Quantity of products processed

$$= \{\sum_{p=1}^{N} W_p P_p - [(11.37 \times 10^{-3})M + T + S]\}*Q$$

$$\text{or} \quad \{\sum_{p=1}^{N} W_p P_p - [\mu M + T + S]\}*Q$$

4.13.3 Remanufacturing revenue equation for model 3

Remanufacturing Overheads per unit = $\beta M + T + S$ where M is Manufacturing cost and T is Logistical costs and S is disposal cost

Where β = (ΣCost ratios of reprocessing operations)*(1/8+3/16)* (Factor correction for remanufacturing)
= (1)(0.3125)(0.67)
= 209.38×10^{-3}

Where S = Weight per item (landfill cost per unit weight + toxicity landfill surcharge)

Setting P as the selling price of a remanufactured product,

Revenue from remanufacturing

= (Selling price of remanufactured product - Overheads)* Quantity of products processed

$$= \{P - [(209.38 \times 10^{-3})M + T + S]\}*Q$$

$$\text{or} \quad \{P - [\beta M + T + S]\}*Q$$

A worked example below using the Euroset 812 recycling option best illustrates the methodology (see shaded region).

Example (Euroset 812, Recycling option)

Manufacturing cost of the Euroset 812	=	£ 30.00
Takeback cost	=	£3
Type of reprocessing operation required: Disassembly, Cleaning and Packaging		
Cost ratio for disassembly and sorting	=	0.197
Cost ratio for cleaning	=	0.380
Cost ratio for packaging	=	0.181
Total	=	0.758
Correction factor for recycling	=	0.12
Cost of operation	=	0.758 x (1/8) x £ 30.00 x 0.12
	=	£ 0.34
Cost of takeback + disassembly Cleaning + packaging		
	=	£ 3.34
Cost of disposal/ landfill	=	£ 0.0025 (83g @ £30 per ton)
Total overhead	=	£ 3.344
Revenue from sale of ABS	=	£ 0.0674 (337g @ £200 per ton)
Revenue from sale of PCB	=	£ 0.009 (83g @ £12 per ton)
Revenue from sale handset of microphone	=	£ 0.004
Revenue from sale of phone cord connectors	=	£0.04 (4@ 1p each)
Revenue from sale of handset speaker	=	£0.006
Revenue from sale of mixed plastic keys	=	£0.004
Total revenue	=	£ 0.1304
Net revenue per phone	=	£ 0.1304 - £ 3.344
	=	- £ 3.213

4.13.4 Summary

Simulations for model 3 were performed using the Relate 100, Converse 300 and Euroset 812 telephone models for coherency. The results for the resale, recycling and remanufacturing options summarised in tables 4.11 to 4.13 are compared with that obtained using actual estimates. Details of calculations can be found in appendix C.

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Model 3 simulation results of overheads (£)	Actual estimate of overheads (£)
Resale	5.429	5.370	4.600	4.767
Recycling	3.268	4.098	3.135	3.268
Remanufacturing	5.606	6.609	5.418	5.606

Table 4.11 Comparison of simulation results of models 1-3 against actual estimates for Relate 100

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Model 3 simulation results of overheads (£)	Actual estimate of overheads (£)
Resale	14.100	6.770	4.74	4.767
Recycling	8.404	5.846	3.322	3.326
Remanufacturing	14.700	12.375	9.281	9.191

Table 4.12 Comparison of simulation results of models 1-3 against actual estimates for Converse 300

EOL Option	Model 1 simulation results of overheads (£)	Model 2 simulation results of overheads (£)	Model 3 simulation results of overheads (£)	Actual estimate of overheads (£)
Resale	14.100	6.770	4.74	4.683
Recycling	8.401	5.671	3.323	3.237
Remanufacturing	14.700	12.375	9.281	9.012

Table 4.13 Comparison of simulation results of models 1-3 against actual estimates for Euroset 812

The corresponding graphs for tables 4.11 to 4.13 are plotted on figures 4.4 to 4.6 on the following page.

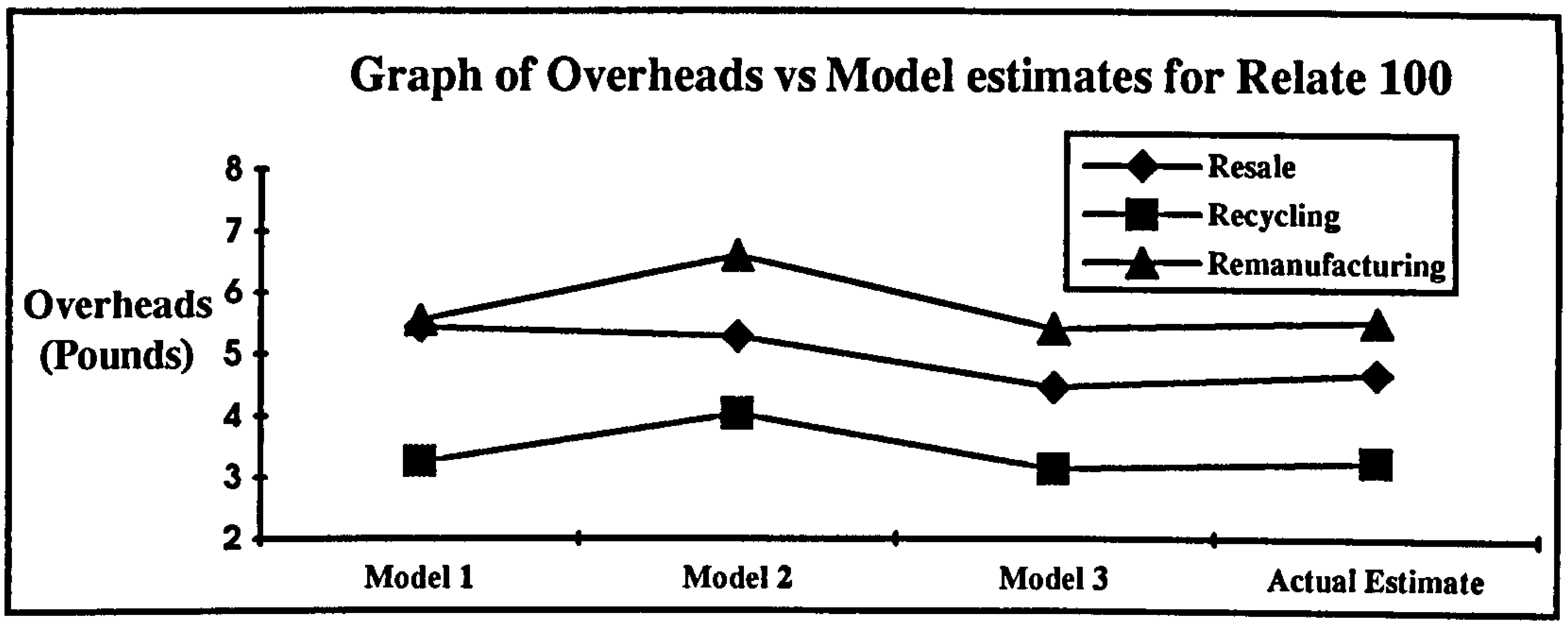

Figure 4.4 Graph of Overheads versus model estimates for Relate 100

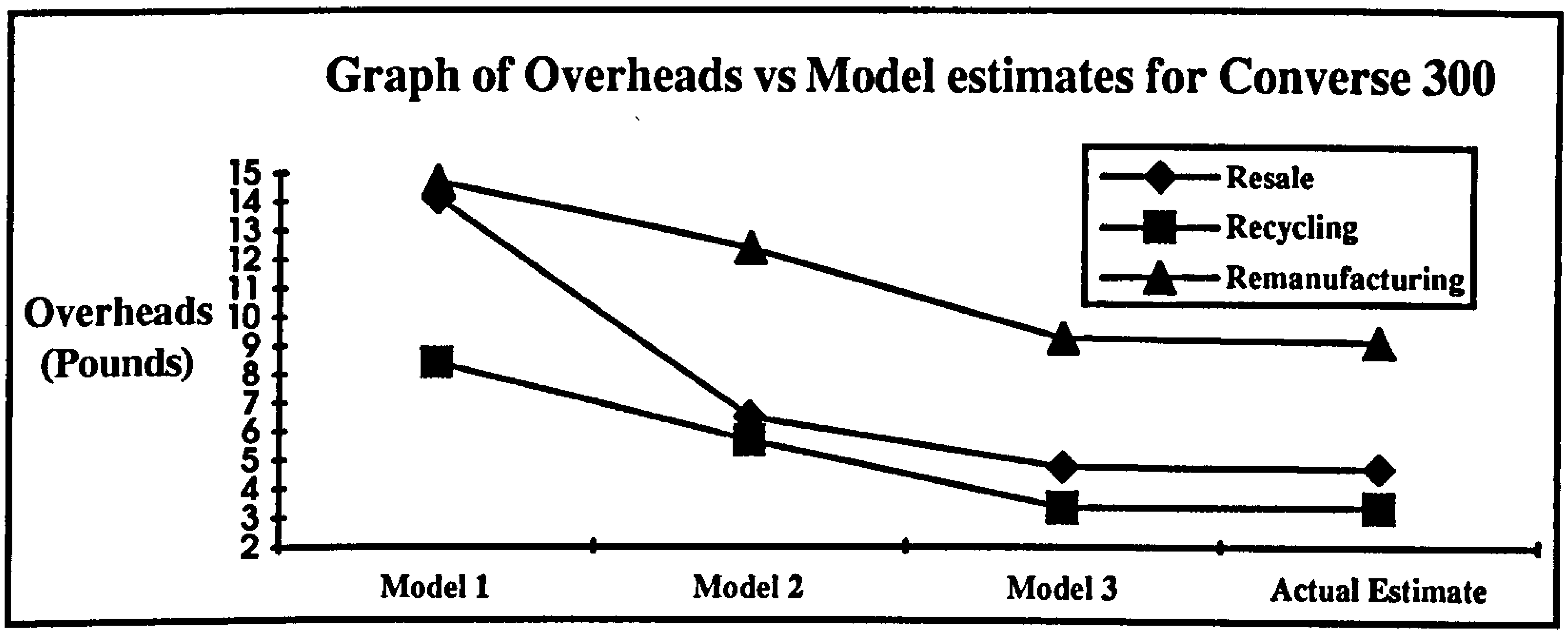

Figure 4.5 Graph of overheads versus model estimates for Converse 300

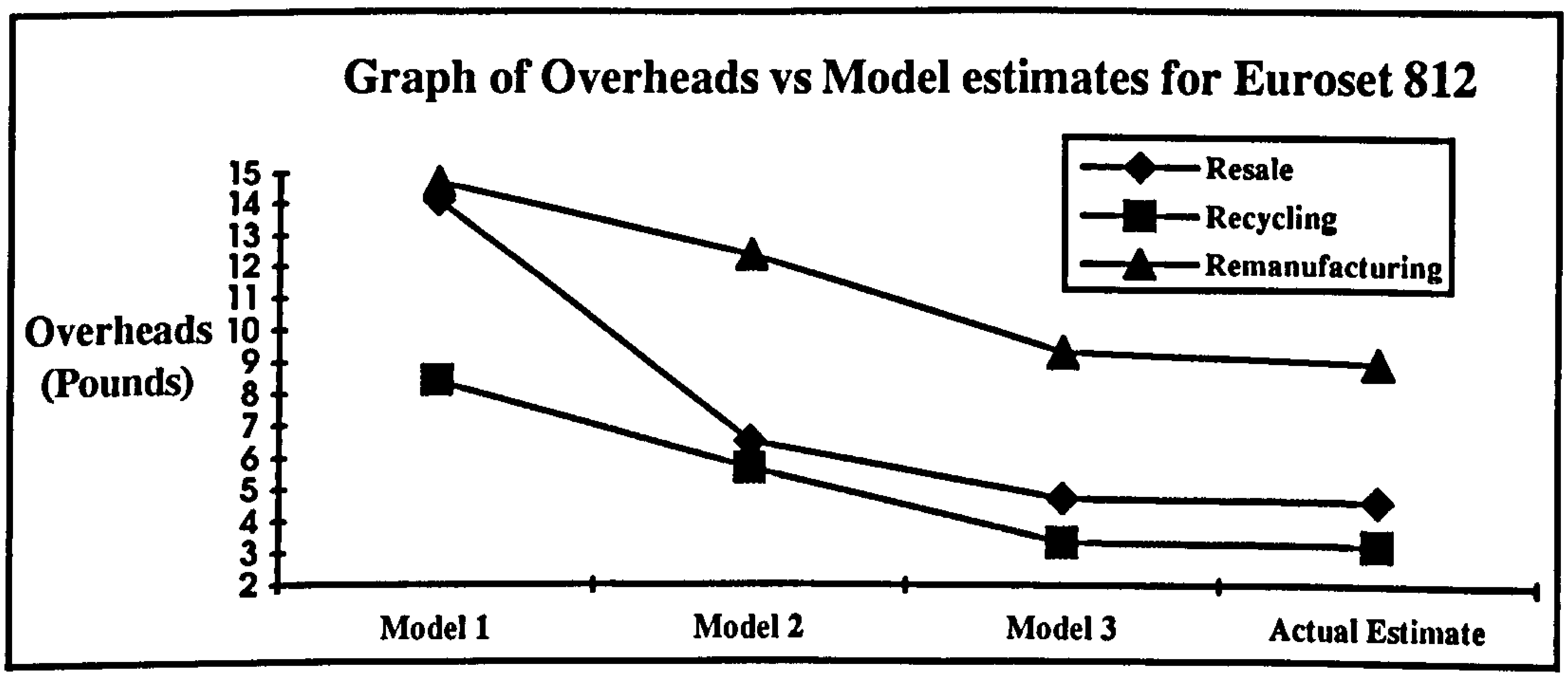

Figure 4.6 Graph of overheads versus model estimates for Euroset 812

Overall observation indicates that simulation outputs from model 3 appear to have come closest to the actual estimates for all product variants compared to the previous two models. Again, resale and remanufacturing are the only profitable options. The initial overheads are highest for remanufacturing followed by resale and recycling for all three telephone models. However, it is apparent that resale still appears to be the most attractive since it offers the greatest revenue with a modest overhead. A summary of the equations derived for model 3 is represented in table 4.14 with symbol definitions as those presented earlier in model 1 (see table 4.1).

End of Life Options	Π_{New}	Π_{Option}	$\Pi_{Profit} = \Pi_{New} + \Pi_{Option}$
Resale	$(P_{Nt} - X_{Nt})Q_{Nt}$	$(P_{Rt+i} - [\alpha M + T]\}_{t+i})*Q_{Rt+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + (P_{Rt+i} - [\alpha M + T]\}_{t+i})*Q_{Rt+i}$
Remanufacture	$(P_{Nt} - X_{Nt})Q_{Nt}$	$\{P - [\beta M + T + S]\}_{t+i}*Q_{t+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + \{P - [\beta M + T + S]\}_{t+i}*Q_{t+i}$
Upgrade	$(P_{Nt} - X_{Nt})Q_{Nt}$	$(P_{v,t+i} - \gamma_{v,t+i}M)Q_{v,t+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + (P_{v,t+i} - \gamma_{v,t+i}M)Q_{v,t+i}$
Recycle	$(P_{Nt} - X_{Nt})Q_{Nt}$	$\{\sum_{p=1}^{N} W_p P_p - [\mu M + T + S]\}_{t+i}*Q_{t+i}$	$(P_{Nt} - X_{Nt})Q_{Nt} + \{\sum_{p=1}^{N} W_p P_p - [\mu M + T + S]\}_{t+i}*Q_{t+i}$
Scrap		$\tau M + \sum_{j=1}^{n} W_j(Y_j + J_j)$	

Table 4.14 Model 3 equations for each end-of-life route

Although the simulations suggest that resale and remanufacturing are the only profitable options, they will however be highly dependent on the availability of the second market and also the type of product intended for reuse. The Relate 100 telephone for example performed well in this aspect as there are established resale markets such as Poland and the Eastern European bloc countries while on the other hand, the Converse 300 model was never considered for resale purpose. Other factors such as the overall green culture of the market place and other economic and legislative drivers are essential influence over its success. These drivers are necessary and often can only be enforced successfully by authorities external to the company. The current absence of these drivers means that EOL benefits cannot be harvested from the best (ecologically) designed product and may just as well be landfilled as normal.

4.14 Mixed strategy model

Since a mixed strategy is necessary to generate any revenue, it appears that resale, remanufacturing and recycling strategies may have to be taken as a combined activity perhaps in most cases for telephone EOL reprocessing. Even then, this combination may only be marginally profitable due to high takeback cost, it is likely that EOL reprocessors carry out a much higher proportion of resale and remanufacturing (both to domestic and foreign markets) than previously anticipated and that this is increasing. Profits for resale and remanufacturing may be used to cover for any other financial losses in the recycling business. Such mixed strategies may be represented by the following equations:

$$\text{Average revenue} = \alpha(\text{Rev Recycle}) + \beta(\text{Rev Remanufacture}) + \gamma(\text{Rev resale}) \qquad (4.8)$$

where

$$\alpha = \frac{\text{Volume Recycled}}{\text{Total Volume}}, \beta = \frac{\text{Volume Remanufactured}}{\text{Total Volume}} \text{ and } \gamma = \frac{\text{Volume Resale}}{\text{Total Volume}}$$

$$\text{and that } \gamma = 1-(\alpha+\beta) \qquad (4.9)$$

Equation (4.8) allows the calculation of a mixed strategy revenue by varying α and β based on the average revenues of recycling, remanufacturing and resale. Complete derivation of equation (4.8) can be found in appendix B. Sensitivity analyses were performed for α and β values to determine the revenues with varying sets of takeback costs for each telephone model as depicted in figures 4.7 to 4.9.

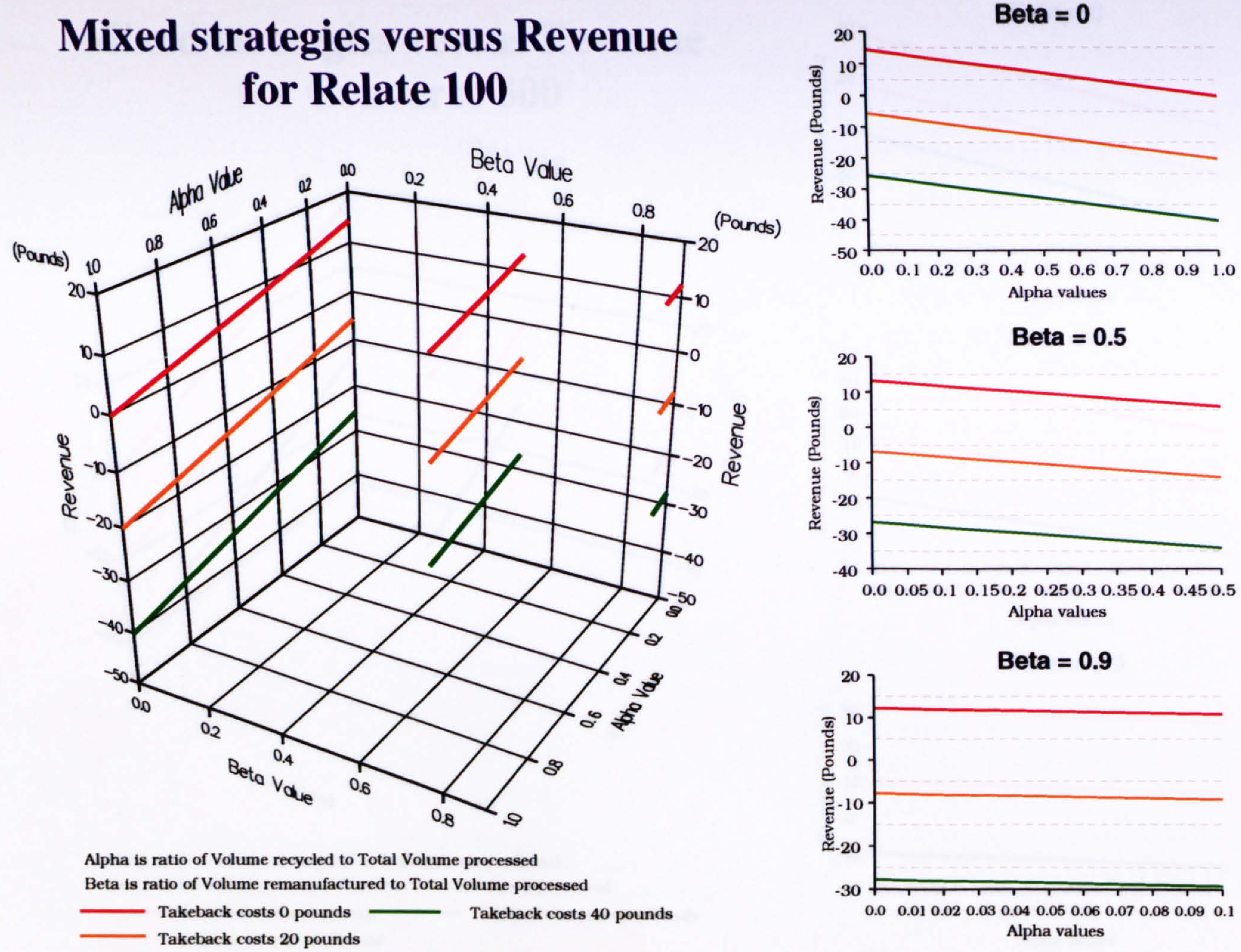

Figure 4.7 Graph of mixed strategies versus revenue for Relate 100

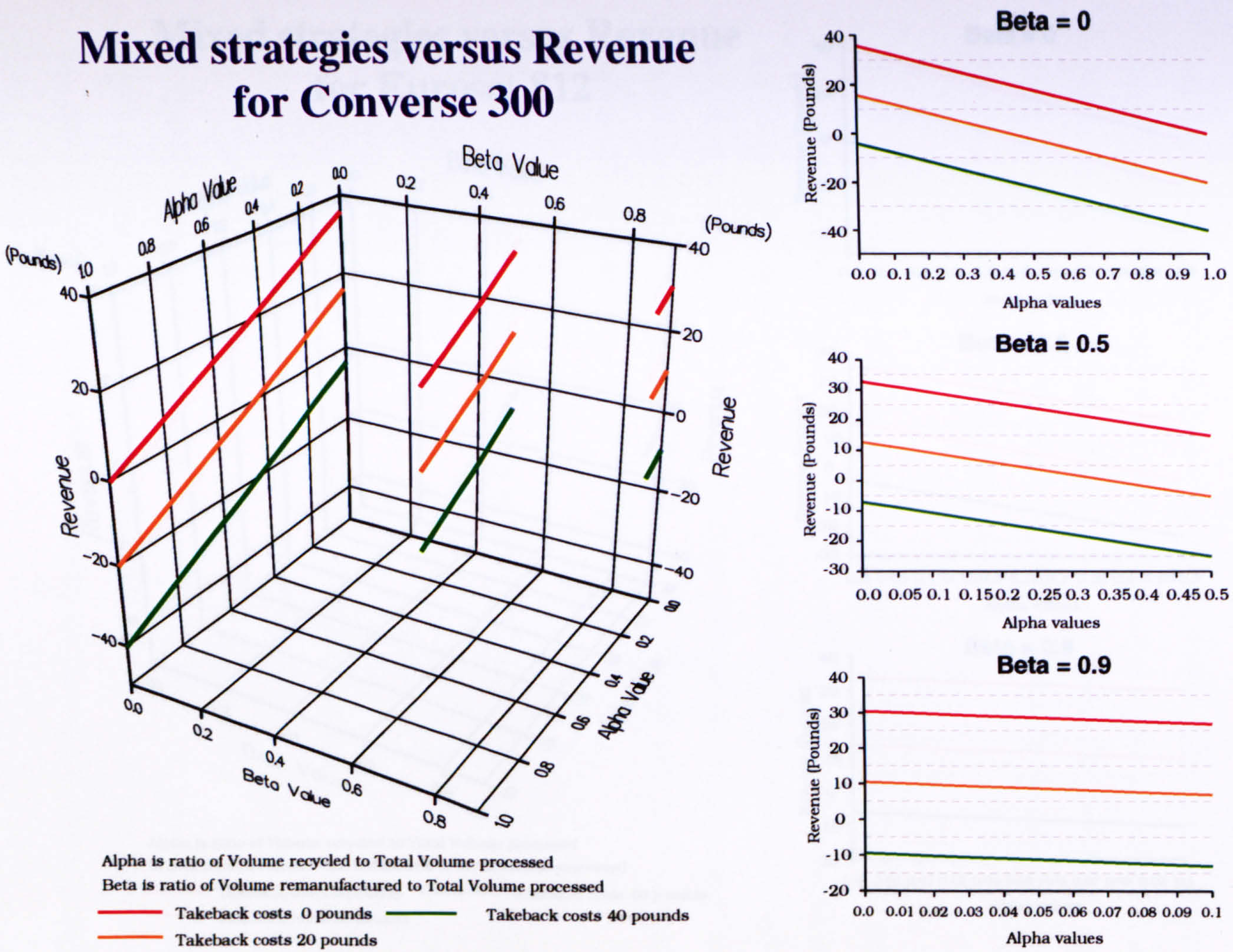

Figure 4.8 Graph of mixed strategies versus revenue for Converse 300

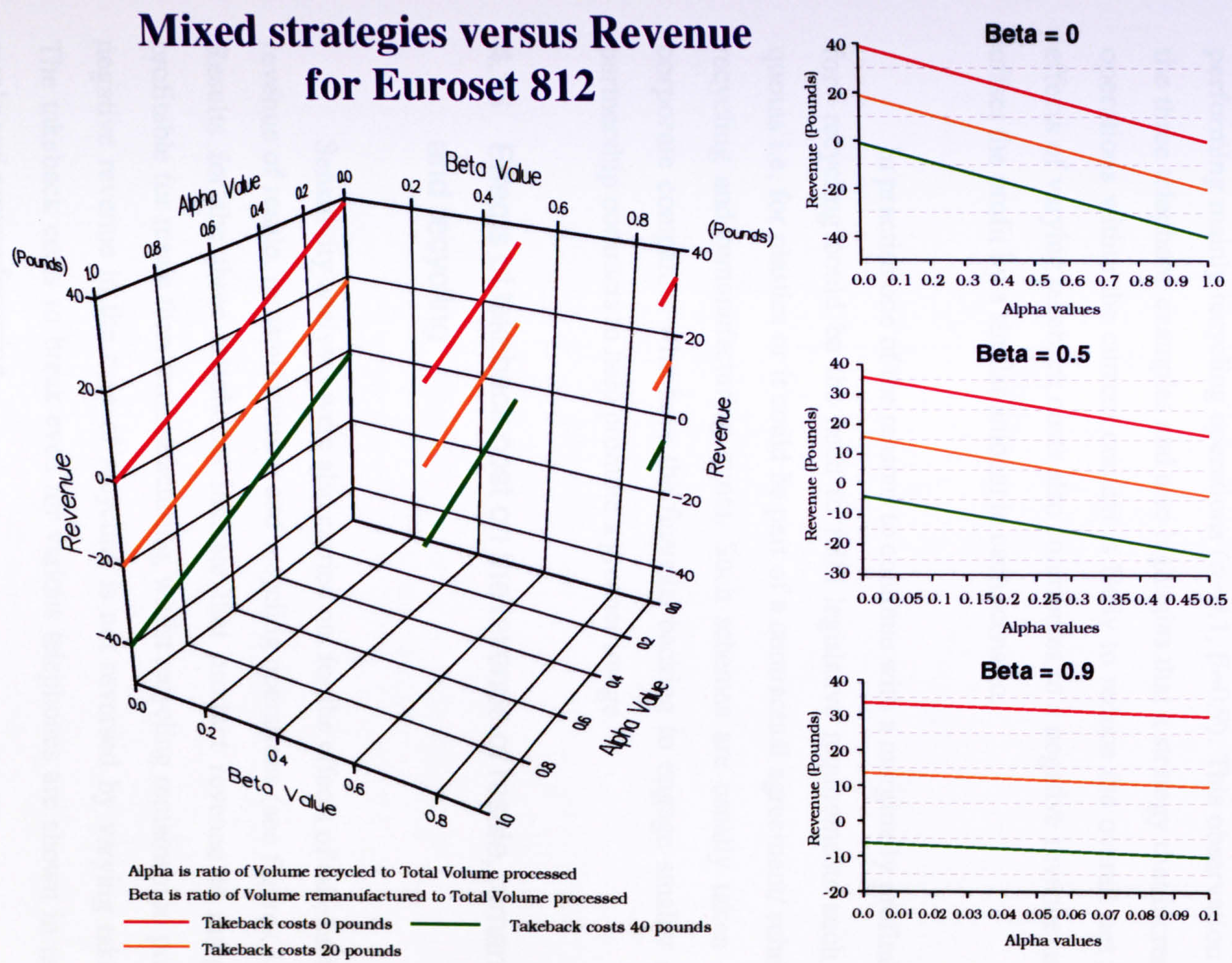

Figure 4.9 Graph of mixed strategies versus revenue for Euroset 812

Sensitivity analyses were carried out using a mixed strategy of three sets of remanufacturing considerations (β=0, β=0.5 and β=0.9) over a range of α values for recycling ($0 \leq \alpha \leq 1$). The corresponding γ value for resale is calculated using equation (K). The overall analyses indicated the maximum revenue generated appears to be considering resale activities alone (α=β=0) while least profit is obtained by performing mainly recycling operations (α=0.1, β=0.9). This observation is true for all the three telephone examples and also highlights that a strategy that increases recycling operations within the current context is likely to reduce the overall net revenue. The effects of varying takeback costs also contributes to a negative revenue and appears to offset the profit by a similar amount in each scenario.

In practise one of the reasons to continue with a marginally profitable operation for recycling could be the need to fulfil legislative requirements such as recycling quotas i.e. for plastics or it could be part of a contractual agreement/ scheme to fulfil a recycling and remanufacturing quota. Such schemes are usually taken on by larger corporate companies who have the financial backing to engage smaller companies in partnership contracts to help promote a greener image.

4.15 Effects of takeback cost on the revenue of resale, remanufacturing and recycling

Sensitivity analyses were also carried out for the effects of takeback cost on the revenue of resale, remanufacturing and recycling operations (see figures 4.10 to 4.12). Results for the three telephones indicate that product revenue is marginally more profitable for resale than remanufacturing, whilst recycling remains non profitable. The negative revenue in the case of recycling is not reversed by varying takeback costs. The takeback costs to break even for various telephones are shown in table 4.15 for resale and remanufacturing.

Telephone models	Takeback cost to break even (£)	
	Resale	Remanufacture
Relate 100	12.853	12.014
Converse 300	34.303	29.879
Euroset 812	37.387	33.058

Table 4.15 Takeback cost to break even for various telephones

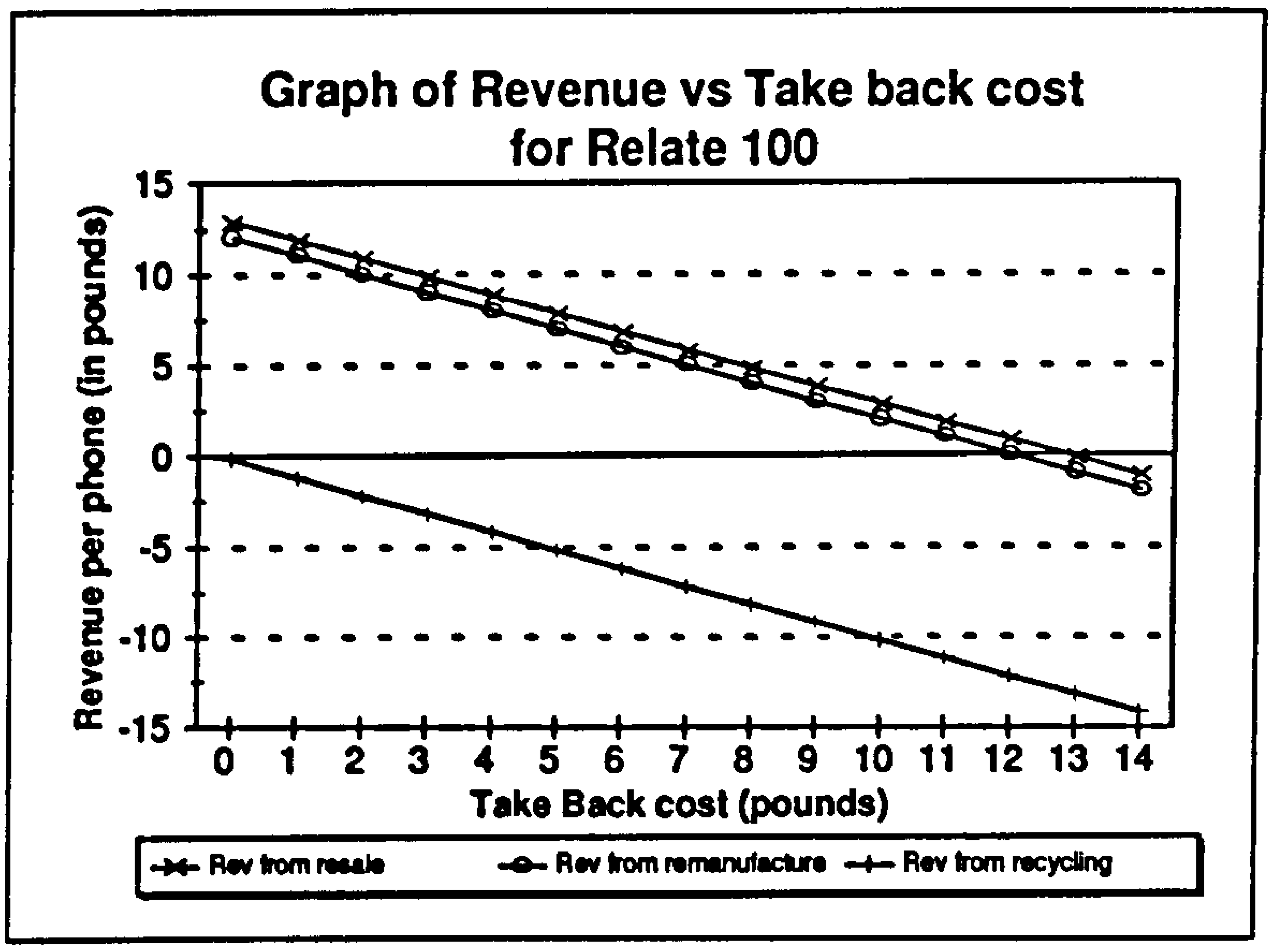

Figure 4.10 Graph of revenue versus takeback cost for Relate 100

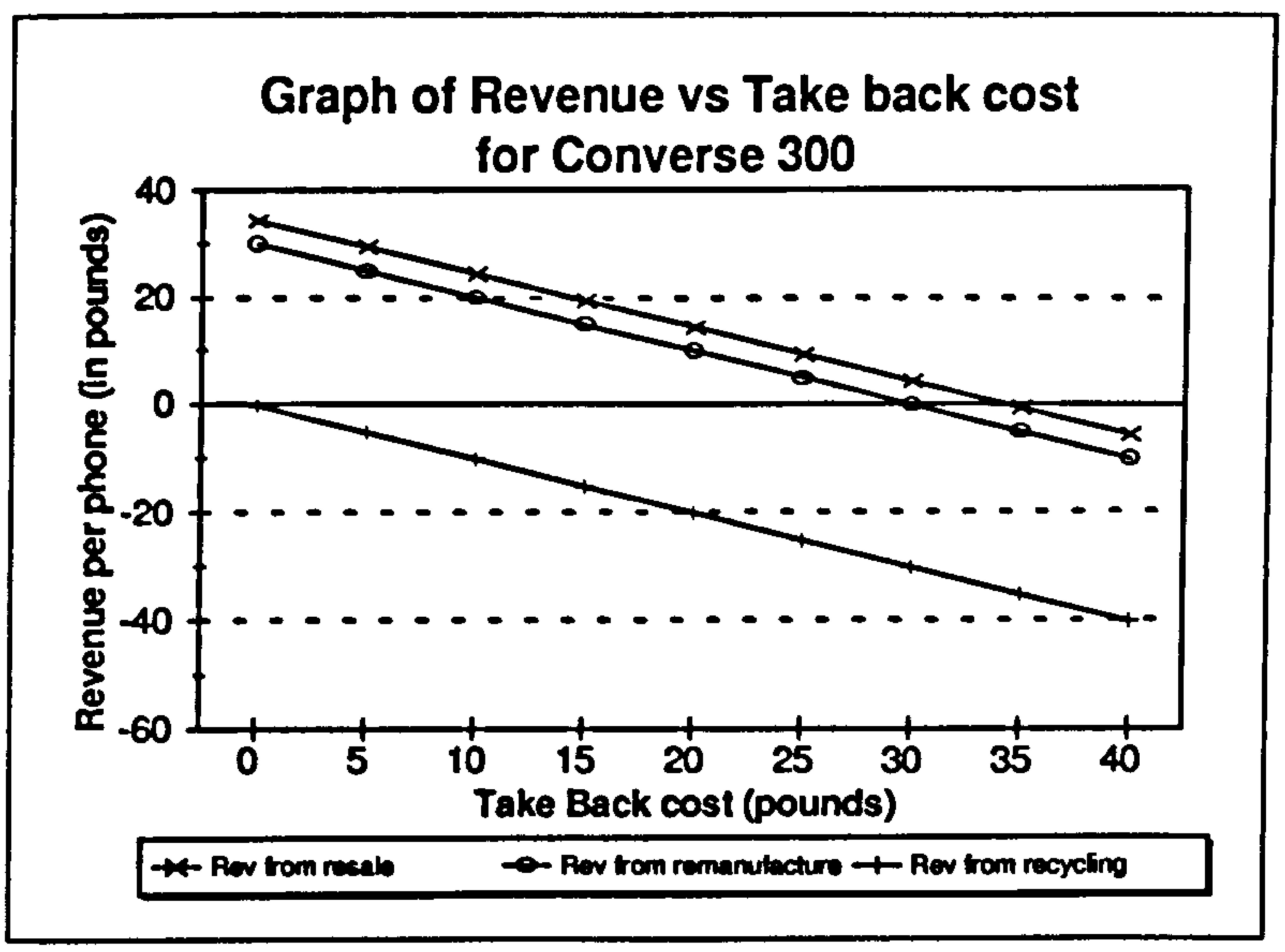

Figure 4.11 Graph of revenue versus takeback cost for Converse 300

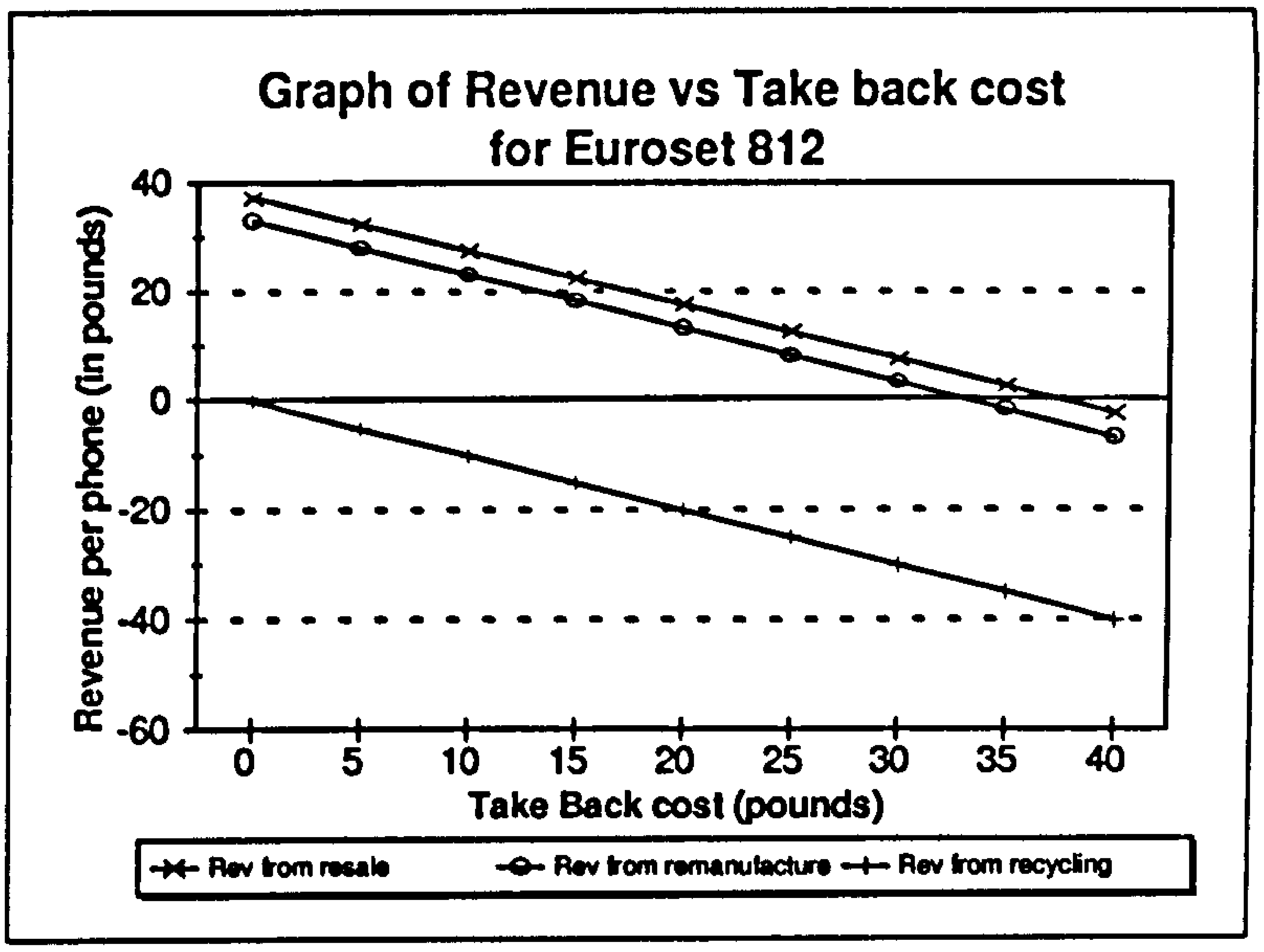

Figure 4.12 Graph of revenue versus takeback cost for Euroset 812

4.16 Discussion

4.16.1 Impact of design changes on disassembly costs

It has been assumed that older products are usually less green and hence would probably cost more to reprocess when they reach their end-of-life. The effects of design changes on the financial impact of EOL operations have been modelled based on a comparative study of the Relate 100, the Euroset 812 a newer ecologically designed product and the Converse 300, the oldest of the 3 telephone models. The outcome of disassembly and sorting costs in table 4.16 reflect the trend in the ease of dismantling arising from a newer design - the Euroset 812 represents the best in this aspect (least cost) whilst the Converse 300 cost most to disassemble. However, the difference in overheads generated between the 3 cases are only in the order of about 10 pence, not very significant amounts in absolute terms. This is again observed in the total overheads and revenue generated from recycling the telephone materials in table 4.17. Although the Euroset 812 represents the best in class of the 3 models (reflected again by the lowest overheads incurred), this is however compromised by its capacity to generate the least revenue in terms of materials recycling. Again, the cost/ revenue differences in absolute terms between the telephones are small and this also suggest that telephone products which are optimised for EOL may not have much cost saving impacts as may be expected.

	Relate 100	Converse 300	Euroset 812
Per unit disassembly and sorting cost for remanufacturing/ recycling	£0.0870	£0.1496	£0.0604

Table 4.16 Per unit disassembly and sorting costs for remanufacturing/ recycling for various telephone models from actual estimates

EOL Operation	Relate 100		Converse 300		Euroset 812	
	Total overheads	Revenue	Total overheads	Revenue	Total overheads	Revenue
Recycling	£3.268	£0.1374	£3.326	£0.1547	£3.237	£0.1304

Table 4.17 Per unit overheads and revenue for materials recycling for various telephone models. Data from actual estimates.

4.16.2 Effects of raising disposal taxation

Figure 4.13 shows the disposal costs per ton for various telephones based on the costs to break even for recycling. It is clear that these figures appear to be about 180 times higher than the current disposal levy of £30 per ton. This represents a taxation figure to drive towards a particular EOL reprocessing route. It should be recognised that the recycling option requires a levy of approximately £5400 per ton to recover its costs. However, the flip side of setting such a high taxation level is not without it's pit falls - illegal dumping is likely to be a typical offshoot problem. This also exposes the limitation of imposing stringent legislation in favour of certain environmental concerns.

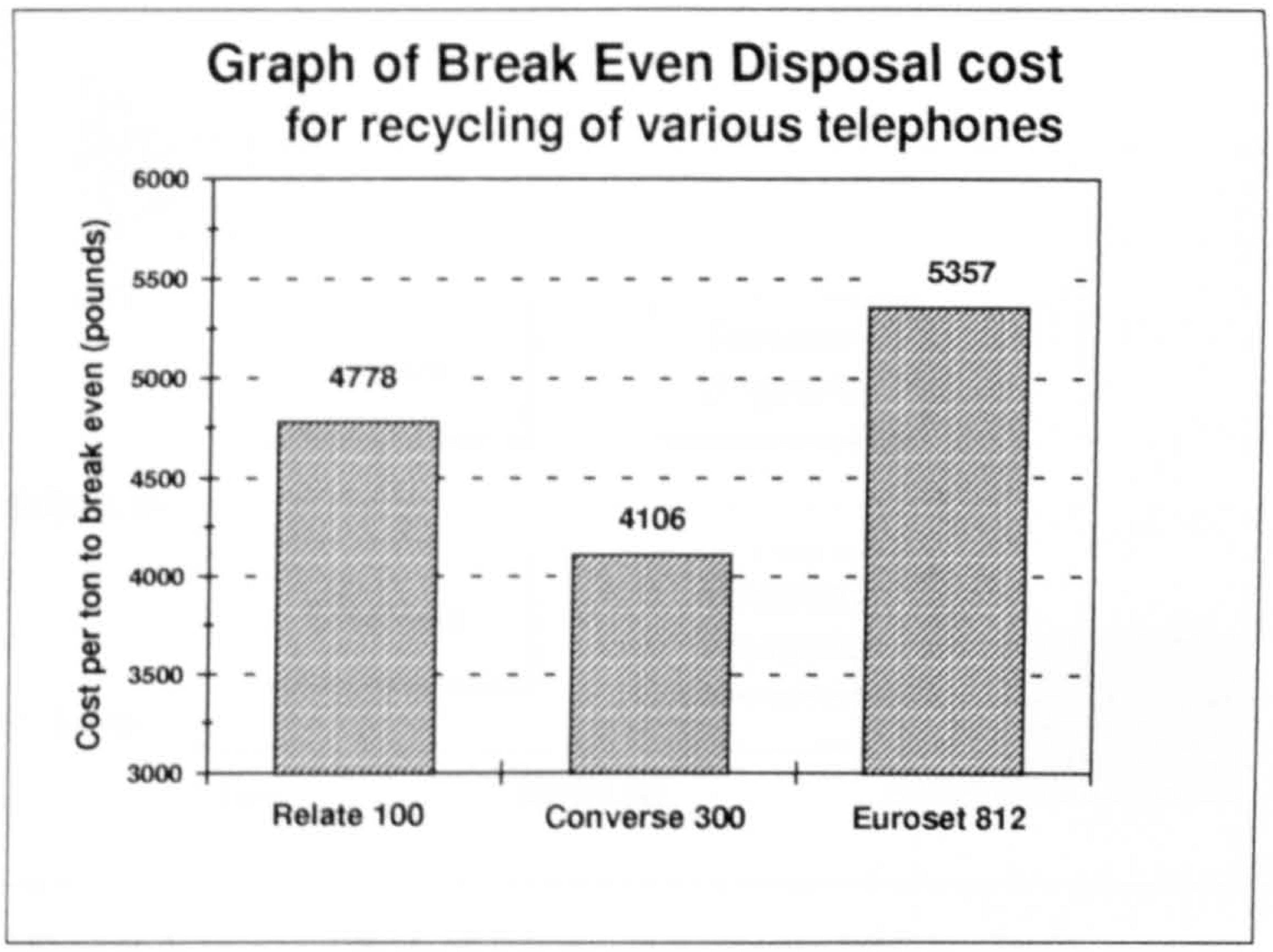

Figure 4.13 Graph of break even disposal costs for recycling of various telephones

4.16.3 End-of-life strategy matrix box

The analysis of the modelling work has helped to shape the understanding of the dynamic relationships between the different EOL strategies taken and how their EOL value could be determined by the value added contents of the product. One of the more effective ways to calibrate the value added of products with significant electronic contents is to consider the ratio of the cost of the electronics to the total manufacturing cost of the product i.e. $C_{Electronic}/C_M$ where C is the cost factor and M represents the total manufacturing cost. The telephone studies have indicated that the printed circuit board though low in volume and weight still dominated at least half the manufacturing cost due to its high value when compared to the remaining components. The optimum EOL strategy that could be undertaken is likely to bear a significant correlation to this ratio and the possible routes are depicted in figure 4.14. The EOL matrix box also uses the $(C_{EOL\ value})/\ C_M$ ratio as the other axis.

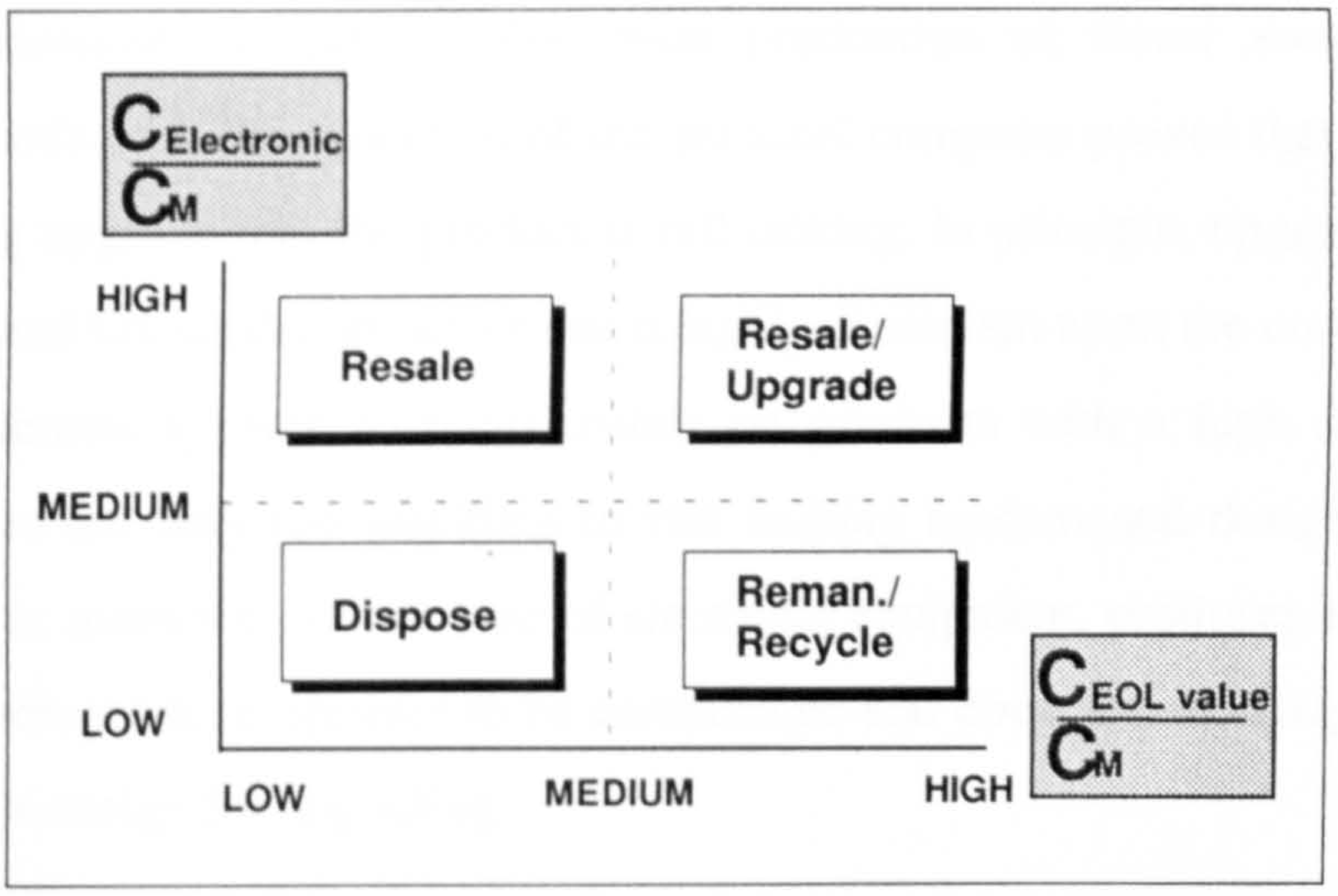

Figure 4.14 End-of-life strategy matrix box

4.16.4 Design hierarchy and upgrade

The modelling work has also led to a better understanding of the hierarchy within design methodologies. The current financial models for telephone products indicate the following hierarchy:

Design for Upgrade >> Design for Resale >> Design for remanufacturing >> Design for recycling

The hierarchy is shaped by considering the potential to extend the life of a product and at the same time its capacity to further generate revenue after it has reached the end of its first life. Initial simulation was performed for upgrading the Euroset 812 model with a fictitious video attachment unit (see appendix C for detail calculations). Table 4.18 indicates upgrading to be the most profitable option. All simulations were based on selling 500 000 products in the first market and 375 000 items from subsequent EOL strategies. Upgrading appears to be the most favourable design methodology for EOL management for the following reasons: (i) it allows the core technology to be retained. This also means total retention of value added and that no further reprocessing is required (ii) the option is profitable since it requires another add-on functional module to be purchased. However, the reluctance by industry to undertake further research into this area is ironically being driven by economic rather than by environmental reasons. The mass production of throw away electronic consumer goods with the exception of the personal computer proves that stimulus for incorporating upgrade into the product is still lacking. In principle, upgrading remains ecologically and financially attractive but is highly dependent upon the core technology - current interests appears to focus mainly on products with a high capital value. Manufacturers are only too unwilling to risk making fundamental design changes to their products, moreover, in the case of electronic equipment, producer responsibility to dispose such products appears to be complicated and does not encourage a positive move towards design for upgrading.

	Upgrade	Resale	Remanufacturing	Recycling
Total revenue (1st market + EOL strategy) (in million £s)	45.63	37.87	36.25	23.84

Table 4.18 Total revenue from various EOL options for Euroset 812

It is also interesting to observe that the hierarchy for different design methodologies may also be highly driven by differences in culture and legislative requirements. This may push manufacturing companies and designers into optimising their products which may be geared towards a particular legislation. These differences in design considerations are perhaps more pronounced in the more advanced European countries. For example, German companies may be more inclined towards disassembly technologies whilst Scandinavian firms may be more interested in the LCA aspects of a product although both countries have strong ecological foundations. This indicates the importance of the generation of international standards. This discussion is also presented in an earlier publication by the author [Low 97].

4.16.5 Other related issues

Initial modelling has also enabled a better visualisation of "how recyclers make money", distinguishing the more from the less profitable operations and may also suggest the direction of the overall business strategy. Through personal communication with various EOL reprocessing plant operators, it is apparent that each is driven by their own business viewpoint which may or may not be sensitive to the overall ecological concern. For example, disassemblers are not likely to welcome the resale route as it robs them of business opportunities; service providers such as BT, are more than willing to incorporate green aspects into their products but however at the expense of companies who manufacture them (assuming that greener products generally command a higher premium).

Consideration of the financial models have also highlighted the relative costs of each option and the amount of added value retained. These costs can be viewed with respect to a more subjective consideration of eco-friendliness, attractiveness to customers, manufacturing companies as well as to service companies. This allows the following observations made in the context of a number of commercial viewpoints.

4.16.5.1 Relationship of retention of value added to cost factors

The optimum end of first life strategy from an environmental viewpoint is to retain as much value added in the product as possible but at minimum cost provided the market still demands the product. The options of upgrading and reselling offer the highest retention in value added while scrapping and recycling provide the least value, as depicted in figure 4.15. The cost axis shows the relative costs of each EOL strategy determined by ranking the coefficients of the costs in the models ($\gamma>\beta>\mu>\alpha>\tau$). The proportion of the value added is variable depending on the extent of remanufacturing, as indicated by the vertical arrows. Although cost recoveries may not always be possible, the difficulties of determining the sizes of the resale and remanufacture market make these difficult to estimate. The horizontal arrow for upgrade indicates that cost of the operation is highly dependent on the functionality of the attachment(s) to the functional core.

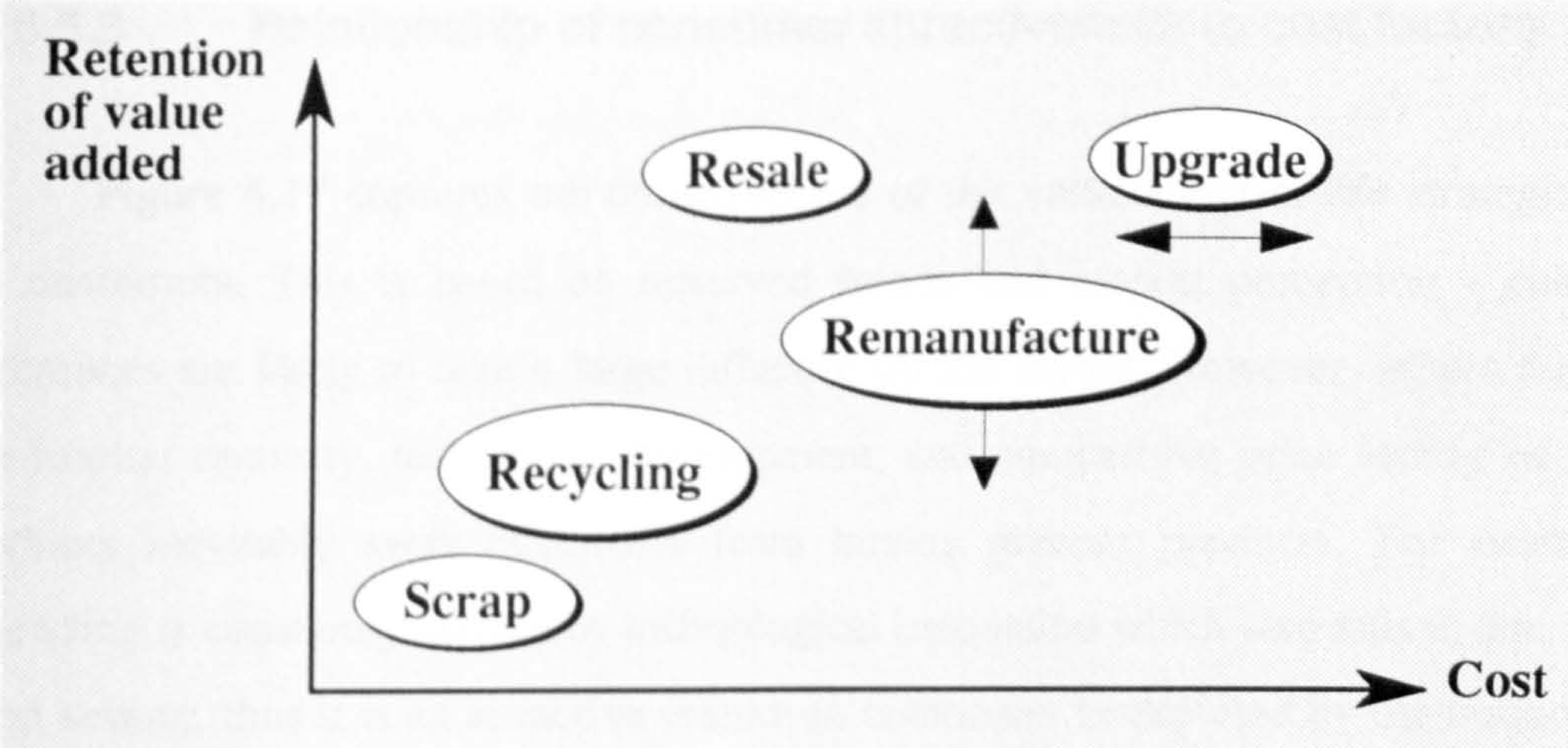

Figure 4.15 Relationship of retention of value added to cost factors

4.16.5.2 Relationship of Eco-friendliness to cost factors

The eco-friendliness relationship between the 5 EOL strategies in figure 4.16 takes into account the energy used for the operation and the damage/ pollution factors to the environment. It may be taken as a "greenness" measure. The most green options appear to be resale as well as remanufacturing while recycling comes next since more energy is consumed and pollution takes place. Upgrading involves manufacturing a new product, thus the extent of eco-friendliness will depend on process conditions, as indicated by the vertical arrows.

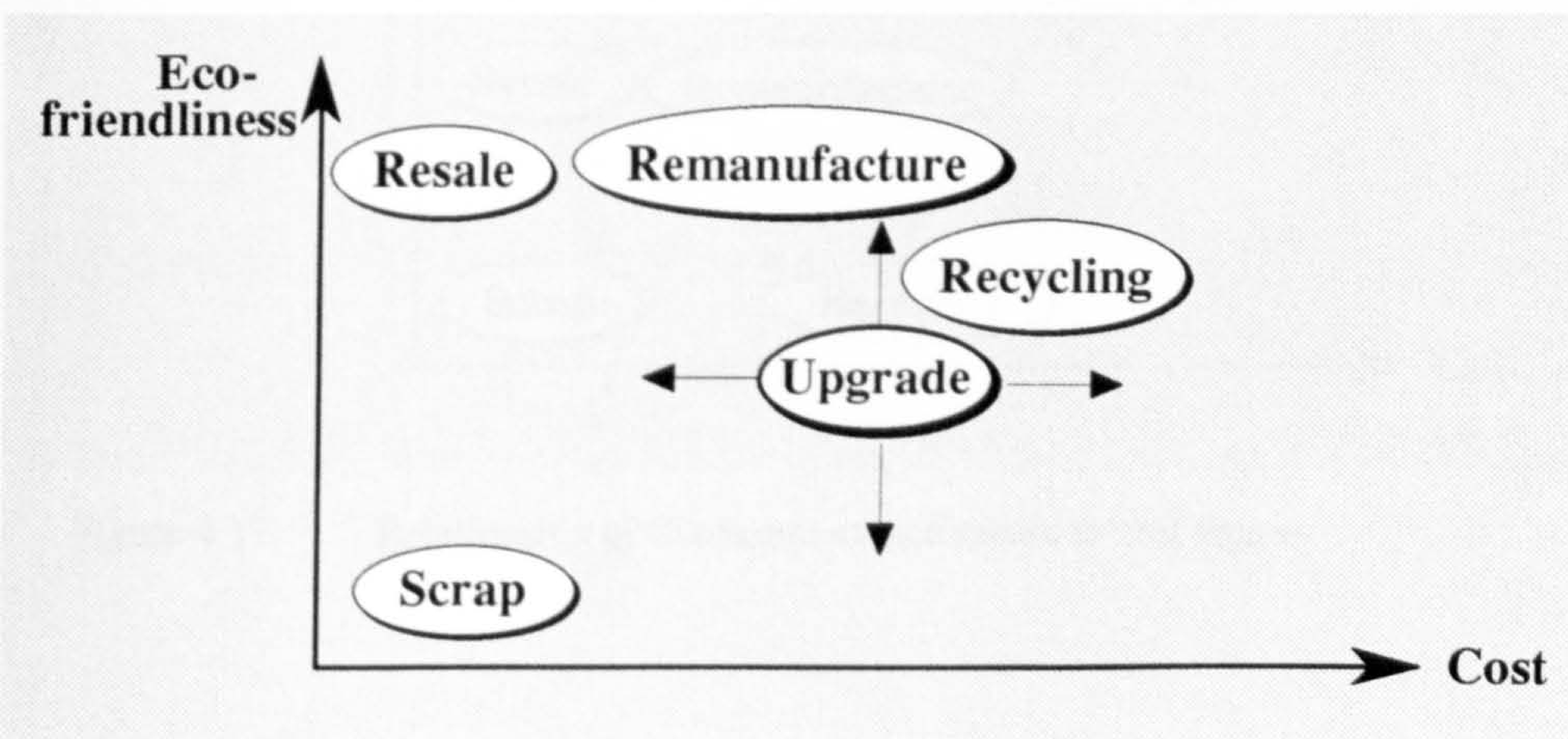

Figure 4.16 Relationship of Eco-friendliness to cost factors

4.16.5.3 Relationship of consumer attractiveness to cost factors

Figure 4.17 captures the attractiveness of the various end-of-life strategies to the customers. This is based on observed trends and market perception - cultural differences are likely to take a large influence on the layout. However, others factors like market maturity, technology development, and competitive price setting of new products inevitably sway customers from buying greener products. For example, upgrading is constantly driven by technological innovation which also falls in line with trend setting, thus it is an attractive feature to customers as depicted by the horizontal arrows. Remanufactured and resold products are usually perceived as lower technology goods. Given similar functionality to a new product in a refurbished model, customers do not easily equate life extension to environmental friendliness - the market in this case is likely to be very price sensitive. Recent media exposure regarding recycled products such as paper and glass have led to a change to greener shopping habits even though this means paying more. The dotted arrows for recycling in the figure indicates customers are willing to pay a higher premium for a greener product given the appropriate environmental marketing.

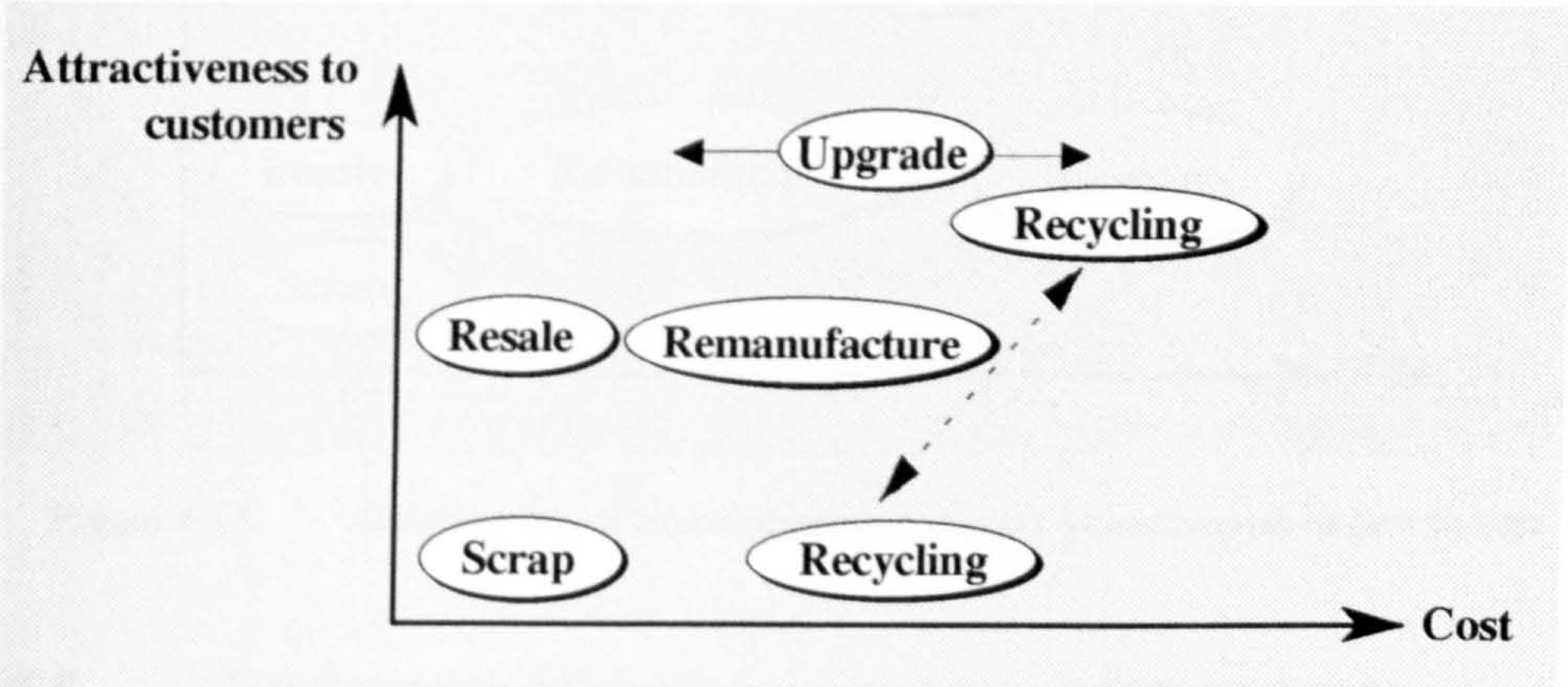

Figure 4.17 Relationship of Consumer attractiveness to cost factors

4.16.5.4 Relationship of manufacturing company attractiveness to cost factors

One of the main aims of a manufacturing company is to competitively capture a target segment of the market whilst trying to achieve a healthy profit margin. Apart from upgrading, the remaining EOL options do not appear to be particularly attractive to manufacturing companies (see figure 4.18). Resale operations for example, tended to capture a share of the same market segment; remanufactured products may produce similar effects, especially if the refurbished parts are reused in similar products. Original equipment manufacturers (OEMs) could arguably put a premium on their products as "compensation" to the potential loss of profit to the second market whilst allowing market forces to generate competitive pricing strategies. Though putting a premium price tag will unlikely be condoned by smaller enterprises, it may be more acceptable to bigger corporate companies who are more keen to build a greener image.

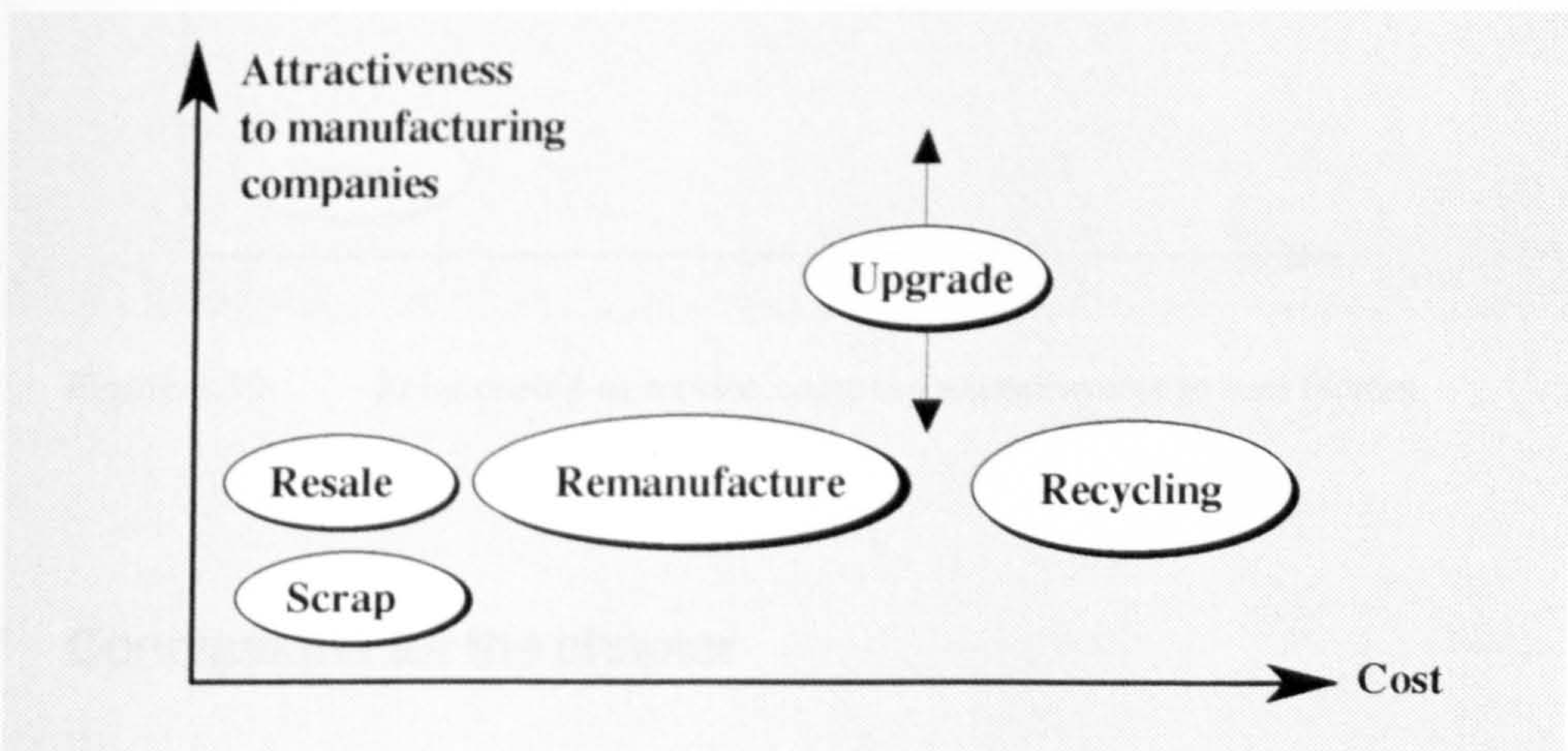

Figure 4.18 Relationship of manufacturing company attractiveness to cost factors

4.16.5.5 Relationship of service company attractiveness to cost factors

Service companies are concerned with providing both convenient, efficient and flexible service(s) to their end-users. The attractiveness of various EOL options in relation to cost factors are depicted in figure 4.19. The EOL options are more attractive to a service company because having a green reputation is likely to boost the market competitiveness. In the case of a telecommunications provider such as BT, this has led to a push for greener specifications from manufacturing companies for their products. This may also be promoted through the use of recycled materials as well as remanufactured parts. The upgrade operation is least attractive because it relies on core technology which appears to detract from the use of newer technology being promoted by the service company. This may be observed in the telecommunications sector where technology advances normally make upgrades expensive and not as efficient as buying a new product.

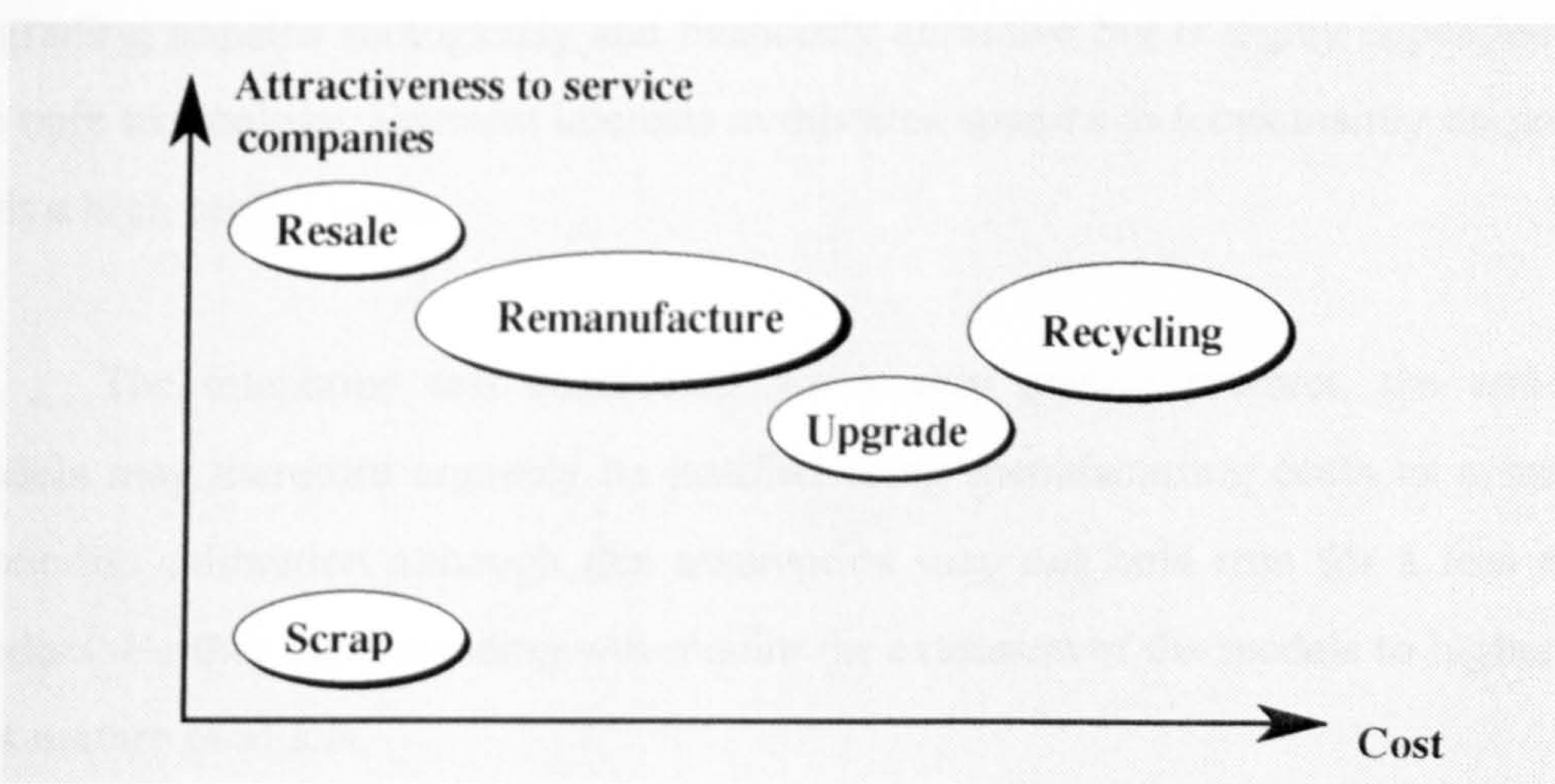

Figure 4.19 Relationship of service company attractiveness to cost factors

4.17 Conclusions for the chapter

This chapter has presented currently accurate financial models of recycling, remanufacturing and resale for a number of telephones with different value add. These are calibrated by an understanding of current commercial practice. A combination of these models describes the profitability of mixed strategies with takeback cost. This work suggests that the product revenue of the telephones under study appears to be larger for complete resale than for remanufacturing, whilst recycling remains non profitable. In a similar mixed strategy scenario involving these three EOL options, the maximum revenue generation involves resale activities alone while least profit is obtained by performing mainly recycling operations. It is also observed that a strategy that increases recycling operations within the current context is likely to reduce the overall net revenue. The effects of increasing takeback costs also contributes to a negative revenue gradient and will offset the profit margin by a similar amount in each scenario. The model however addresses upgrading only to a limited extent as the telephone products under study do not have upgrading routes. Although upgrading appears to be the most favourable design methodology for EOL management, there are technical issues associated with upgrade that require modular product architectures to be created. However, the reluctance by industry to undertake further research into this area is ironically being driven by economic than by environmental reasons. In principle, upgrading remains ecologically and financially attractive but is highly dependent upon the core technology - current interests in this area appears to focus mainly on products with a high capital value.

The telephone sets considered are a very mature product, the end-of-life models may therefore arguably be justified using manufacturing costs as a basis for economic calibration although this assumption may not hold true for a less mature product. Further understanding will require the extension of the models to higher value less mature products.

CHAPTER 5

Conclusions

5.0 Introduction

Conventional business and manufacturing processes have been concerned with marketing and making products that rarely go beyond their first life. It is only in recent years that tightening legislation on the environment has caused businesses to re-examine their priorities with respect to the environment. This has quickly led to further interest in developing techniques that address waste reduction and more recently, product life extension. In manufacturing industry, a growing number of products are currently being designed taking into account life cycle considerations. However, the move towards "green" design and technology has been slow. This has been hindered by many complex and interrelated issues such as those associated with finding a compromise between the requirements of legislation, the limitations of environmentally oriented technology and business drivers. Consideration of these broader issues within the literature review chapter of the thesis has indicated that work should be focused on the design understanding required to allow product life extension as well as evolving existing strategies to address the reprocessing of used products.

The core of this thesis therefore concentrates on the design and financial aspects of telecommunications products at their end-of-life, using telephone products as an exemplar to explore the issues from a realistic starting point. The following sections briefly summarise the conclusions drawn from the literature survey and the core contributions from the other chapters of the thesis (chapters 3 and 4) before ending with suggestions for future work that build upon the limitations of the present work.

5.1 Literature review

Most public domain literature in the broad environmental area has been produced within the last 10 years, however it is only in the last five years that a significant volume of material focusing on electronics and the environment has been generated, as a direct consequence to the growing interest in the environment and industrial impacts upon it. These observations indicate the relative infancy of research in the "green" area. There are therefore many relevant issues to be explored and there has been some lack of a coherent research framework for the area. The work of this thesis therefore stems from the necessity to recognise and focus on the germane issues concerning electronics and the environment. A wide literature review, as presented in the thesis, was therefore required to overview the area.

The review first identified the impetus behind current paradigm shifts towards sustainable development and clean technology (section 2.0). This macroscopic discussion was then brought into narrower focus by examining at the environmental, legislative and economic drivers within the electronics industry (section 2.1). The benefits and potential risks of adopting environmental standards such as ISO 14000 and EMAS on businesses were next examined (section 2.2). The review then departed from legislative and commercial themes to explore two major technological strands: life cycle assessment techniques (section 2.3) and design for 'X' where 'X' is a desirable product characteristic such as manufacturability or disassemblability (section 2.4). Other environmental issues such as health and safety in the workplace and organisational aspects of environmental management have no direct relation to the work and hence have been excluded from the review.

The review highlighted the complex issues surrounding the significant interaction between legislation, technology and business. Although it is recognised that other challenges exist within any environmental framework this work focuses on this interaction. Whilst literature abounds in certain areas, such as the legislative-business interaction drivers, the review revealed a lack of published materials in other areas. These predominantly concern the development of the infrastructure surrounding the end-of-life electronics industry and particularly the economics of reprocessed products. This, together with the evolving interests of the industrial collaborator and the international evolution of understanding in the area, has therefore led to the themes of the work reported in this thesis.

5.2 Product design evaluation from the end-of-life perspective

The body of the thesis has two themes; the first theme explores design issues related to the end-of-life management and is presented in chapter 3. Technological insights into product design from the end-of-life perspective were gained by first examining disassembly techniques and comparing them with conventional design-for-assembly methods. The goals of the two methodologies were contrasted at the conceptual stage of product design and the results shown in table 3.2. The application of the two methodologies as part of an optimum end-of-life strategy will reflect a compromise likely to be dictated by the product type, its maturity in the market and the intended end-of-life route. For example the design strategy for telephone handsets will be different from that of a stereo walkman. The former represents a mature product with an established reprocessing infrastructure whilst the latter is smaller and has little end-of-life value and therefore the need for disassembly optimisation is much less critical.

A more detailed product design evaluation from the end-of-life perspective was then carried out via a benchmarking case study of eight telephone handsets from Europe and the Pacific Rim. These designs represented a significant sample of those sold in the UK and Europe, and ranged from machines where end-of-life aspects appeared to have been considered to machines that had solely been manufactured for the lowest cost. The contrasting design approaches highlighted both design and manufacturing constraints from different geographical and technological backgrounds. One of the contributions arising from the case study is the development of generic design guidelines for telephones from the end-of-life perspective. These guidelines were developed by considering the ease of disassembly, materials recovery and recycling, and remanufacture and resale. Specific guidelines for disassembly were ranked by taking into account the average time taken for items to be disassembled whilst materials recovery rules are mainly directed towards recycling of the ABS plastic. The benchmarking results of the telephone products against these guidelines indicate that the German products broke the least best practise rules whilst the

Malaysian manufactured telephones broke the most rules (see table 3.15). It was also found that the benchmark performances of the telephones reflected major constraints that were imposed predominantly by design specifications that conflicted with EOL considerations. These mainly affected BT products and arose from specific standard requirements placed by BT.

The design guidelines were further applied to a pager telecommunications device. This product was selected as it contrasted with a desktop telephone in terms of both less product and market maturity and more technology complexity. The pager study indicated that a majority (about 70%) of the telephone design rules were generic when applied to the pager while the remaining rules required more product specific considerations. This also reflects the limitations of the telephone design guidelines for use in general electronic products - and the necessity to fine tune general guidelines to take account of product specific issues.

5.3 The evaluation of the impact for recycling and disassembly on manufacturing costs

Following the design study the work turned to examine the manufacturing cost impacts of improving the performance of individual designs with respect to their end-of-life performance. These manufacturing cost impact studies have been carried out with two companies - one in Wales (Nortel), representing a high cost manufacturing location and the other in Malaysia (Inventec) representing a lower cost high volume production site. This comparison was made to understand of the impact of manufacturing costs on design changes from the viewpoints of two manufacturing companies, each of a different character and also from very different economies and geographical locations. Nortel identified further design for end of life changes could be made with minimum impact on the cost of the telephone, because of careful materials engineering and present policies to produce products that are geared towards end-of-life management. Inventec in contrast identified that such changes would involve significant cost - as reflected in the increase in cost estimates in table 3.16, probably due to a requirement in tooling or machine changes. This indicated the significant issues associated with communicating end-of-life considerations driven primarily by European legislative pressures down the lower cost overseas supply chain.

The largest constraints on manufacturing cost reduction were found to be the external styling of the telephone in combination with some constraints within the BT specification. This particularly affects the layout of the printed circuit board, the most expensive item, given the available space within the housing. This highlights the possibility of considerable improvements in EOL impact by optimising the PCB real-estate available area and height. The impact of design changes manufacturing cost also highlighted reuse without refurbishing as perhaps both the most cost effective and least damaging approach from an overall end-of-life consideration.

5.4 The evaluation of the economic models

The first, design led theme of the thesis, indicated strongly that the economics of end-of-life management affected the design strategies that might be applied. This therefore led to the second theme of the thesis which links the business and technological issues faced in the EOL management of electronic products. The second theme builds on the technological understanding generated in the first theme; the main contribution of this work lies in the economic models presented in chapter 4. The economic models were conceived with the intention of enabling rapid assessment of the trade offs between different end-of-life strategies without having to make too much compromise on accuracy. These models were derived for the strategies of resale, remanufacturing, recycling, disposal and upgrade. The models separate manufacturing, disposal and transport (takeback) costs and assume, in the final complete model, that disassembly and sorting, resassembly, inspection, testing, packaging costs are proportional to final manufacturing costs.

Each model has been matched to current commercial data for a number of telephone models in order to determine appropriate values for empirical constants. The revenue equations for resale, remanufacturing and recycling are summarised in table

5.1 and give an indication of proportion to the manufacturing cost when each EOL strategy is considered.

EOL option	Revenue equation	Legend
Resale	$\{P - [(9.09 \times 10^{-3})M + T]\} * Q$	P:selling price, M:Manufacturing cost, T:Logistical costs, Q:Quantity sold
Remanufacturing	$\{P - [(209.38 \times 10^{-3})M + T + S]\} * Q$	S: cost of remaining components to be disposed
Recycling	$\{\Sigma W_p P_p - [(11.37 \times 10^{-3})M + T + S]\} * Q$	W:Weight per unit,P: Price per unit

Table 5.1 Summary of revenue equations for resale, remanufacturing and recycling

The results of the models indicate product revenue appears to be larger for complete resale than for remanufacturing, whilst recycling remains non-profitable. A mixed strategy model was derived involving these three EOL scenarios, the maximum revenue generation again relates to resale activities alone while least profit is obtained through complete recycling. A strategy that increases recycling operations within the current context is also likely to reduce the overall net revenue. Sensitivity analyses of varying takeback costs indicate a general negative revenue gradient that offsets the profit margin by the same amount for each EOL strategy. Consideration of the revenue generated also indicates the preferred design strategies and helps resolve some of the uncertainties currently faced by decision makers.

The current financial models for telephone products show the following preferred hierarchy of design strategies : Design for upgrade >> Design for resale >> Design for remanufacturing >> Design for recycling. The hierarchy is shaped by considering the potential to extend life and the product capacity to further generate revenue after it has reached the end of its first life. The upgrade option has been addressed only to a limited extent in this thesis as the telephone products under study do not have upgrading routes because of design limitations. In principle, upgrading remains ecologically and financially attractive but it is highly dependent upon the core technology. Current interests in upgradeable products appear to focus mainly on products with a high capital value. Manufacturers are unwilling to risk making fundamental design changes to their products, moreover, in the case of electronic equipment, the reluctance shown by producers to examine the potential to life extension indicates the fear of risks involved in the potential change of consumer attitudes towards a product.

Consideration of the dynamic relationship between the different EOL strategies and their EOL value has led to the generation of an EOL strategy matrix box (see figure 4.14). The layout of the elements within the matrix box is derived by considering the ratios of total cost associated with manufacture to the cost of electronics content and its EOL value. As the optimum EOL strategy that could be taken is likely to be significantly related to these ratios, the matrix box offers the opportunity to rapidly assess the appropriate end-of-life strategies for electronic products. The qualitative understanding of the relative costs of each EOL option was also examined in this work. These costs were viewed with respect to a more subjective consideration of factors such as the retention of the value added in products, eco-friendliness, attractiveness to customers, manufacturing companies as well as to service companies (see figures 4.15 to 4.19). Appreciation of these qualitative issues allow for a more complete assessment of the various EOL strategies from a range of environmental and business viewpoints and thus contributes towards an increased understanding of the overall drivers within the environmental framework.

5.4.1 Limitations of the models

The telephone handsets considered in this study represent a very mature product. The relationship of product pricing to manufacturing cost with time in figure 4.1 shows telephone products are well positioned within this mature time frame. Market pricing for these products are much closer to the manufacturing cost than for newer, perhaps more complex equipment with higher value add. The derived end-of-life models may therefore arguably be justified using manufacturing cost as a basis for economic calibration. Although realistic models have been presented in the context of this work, their application to less mature products may not however yield results with similar accuracy because such products may not have EOL costs that can be estimated based on manufacturing cost projection, as in the current models.

Another limitation of the current modelling approach lies in the estimation of the cost of overheads for reprocessing. The formulation of the equations to calculate the necessary overheads are expressed as a proportion of manufacturing cost and do not implicitly quantify the value added aspects of a product. This problem is reflected in the Converse 300 and Euroset 812 telephone examples - both of which have the same manufacturing cost, the former telephone however supports more functionality and also has more internal components than the latter; therefore it has a higher value add and requires more subsequent reprocessing work. Despite such differences, the projected overheads for both products remained unchanged (see tables 4.12 and 4.13). The absence of considerations in the models given to factors such as country of origin and its associated labour and transport costs in design and manufacture, branding, etc. may account for this limitation.

The major conclusions of the work are, in summary;

- there are complex tensions between environmental, legislative, economic and technological drivers, these are clearly shown in the reprocessing of products,
- generic, best practise guidelines for end-of-life design that can be applied to desktop telephone products,
- calibrated, generalised, relatively simple, economic models that form a tool to link business and technological issues and allow comparison of end-of-life strategies for a range of mature telephone products,
- based upon the economic models, an indication of a preferred hierarchy of design strategies - design for upgrade >> design for resale >> design for remanufacturing >> design for recycling,
- an understanding of how mixed end-of-life strategies can allow economic reprocessing operations,
- an understanding of the complexities associated with the globalisation of manufacture and environmental issues, and,

- an identification of the need to generate more understanding in design for upgrade and for the economic modelling of high added value products where product price is not close to manufacturing cost.

5.5 Suggestions for further work

Two areas are identified for further work.

(i) As previously discussed, the current modelling approach is not likely to yield results of similar accuracy for newer products with higher value add. Factors such as technological obsolescence, brand premium, market loyalty, etc. will become increasingly more significant in such products and consideration given to these factors may require departure from assumptions employed in the present models. For less mature high value added electronic products, mechanisms involved in market pricing are more complex as product pricing in relation to manufacturing overheads becomes even less predictable (see figure 4.1). Extension of the work to such products therefore requires the development of predictive models that capture these important but less quantifiable variables. At the same time, it is also desirable to maintain the simplicity of the design tool to rapidly assess the trade offs between different end-of-life scenarios. It is anticipated that future approaches may depart altogether from the use of manufacturing costs as a basis for economic calibration and other quantitative prediction techniques can be used to address the more buoyant economic issues generated by market forces for less mature products.

Another suggested area for work involves building into existing models the ability to consider the differences between the value add of *mature* products quantitatively. A good starting point to improve the end-of-life models is to compare two telephone products with the same external design but each of a different design origin and manufacture. (Current offerings of some of BT's products have similar external appearances but are designed and manufactured in different geographical locations due to commercial reasons thus allowing opportunities in this area of research). This suggested approach can help identify and further quantify design issues in relation to the overall value add problem, all of which may be incorporated into a second generation end-of-life model.

(ii) Future work can be carried out to further address design for upgrading of electronic products. Two essential types of upgrade exist - hardware and software, of which the latter category appears to be well developed. Software upgrades have found widespread applications in products such as the personal computer (PC) and in other computer controlled domestic appliances like the washing machine, to help drive a variety of energy efficient operation programmes. Developed techniques for hardware upgrade on the other hand have been fairly limited for electronic consumer durables, with the exception of the PC. Hardware upgrade often involves replacing or adding modular machine element, however it usually requires fundamental changes to the core technology. This approach may be unattractive to some manufacturers. Moreover, the exact environmental benefits of an upgradeable product can only be realised through comparative LCA studies which are often complex and expensive. The integration of upgrading strategies into the design alternatives (by either incorporating design guidelines or employing other quantitative methods) without the use of exhaustive LCA methods to achieve both economic and environmental trade offs therefore presents an interesting opportunity for further research.

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APPENDIX A

Size reduction of electronic products - a questionnarie assessment of the moderation of ecological impact by miniaturisation

Introduction

Electronic products are becoming more compact with increased functionality and circuit density. Given legislative and ecological pressures, miniaturisation/ dematerialisation technology appears to be the ideal solution to the reduction of overall materials consumption; this is in agreement with the "Less is best" approach to inventory loading in a LCA impact assessment (see section 2.3.2.3). Other positive effects of size reduction are illustrated by the use of less precious metals in interconnections, a reduction (if not a gradual replacement) of lead solders and other toxic materials in electronic circuitry. However, it remains to be demonstrated that miniaturisation techniques can potentially minimise the ecological impact of electronic products.

The questionnaire approach being used is to attempt to establish the relationships between size and impact at significant stages in the product life cycle for a printed circuit board and its major components. This problem is also being used as a representative problem to study more qualitative methods of impact assessment in an attempt to establish the relationship between the size of a product and its ecological impact. The stages being considered are:

- Bare board manufacturing
- PCB assembly
- Through life and,
- End of life phases

Acquiring and appropriately representing all of this data in a full LCA impact assessment is not practicable: the scope being too wide and data collection is difficult due to its commercial sensitivity. The author has therefore taken another approach, one that is based upon the completion of a graphically oriented questionnaire addressing all aspects of the product life cycle.

The questionnaire surveys 25 different aspects in the life cycle of a PCB examining the effects of varying Board sizes versus Bareboard manufacturing, PCB assembly, Through-life and End-of-life phases. Besides making a simple sketch to demonstrate the relationships between the labelled axes, the respondents were also required to rank the ecological impact on a scale of 1 to 10, and, to indicate the level of confidence of each factor examined.

Results of the questionnaire

Four sets of questionnaires were sent to a number of carefully targetted prominent industrialists in electronics*. A sample copy of the completed questionnaire from ICL and a summary table showing the results (see table A3) is shown at the end of this appendix. The initial results for each respondent are qualitatively summarised as shown in figure A1. The work is also presented in an earlier publication by the author [Low 94b]. In the figure, "+" represents an increasing effect with board size, "0" represents no change in effect with board size, "Step" represents a step change in effect at certain board sizes and, "Exp" depicts an exponential response and "Max" a maximum effect at a particular board size (see figure A1). Relative rankings were performed on column 'A' (ecological impact) and column 'AxB' (Multiplied rating) to contrast possible discrepancies between the two ratings due to varying confidence levels.

*The industrialists who participated in the questionnaire survey were: Mr P Hamilton (ICL), Mr K Murray (IBM), Dr K Snowdon (BNR) and Mr M Burstall (Mayer Cohen)

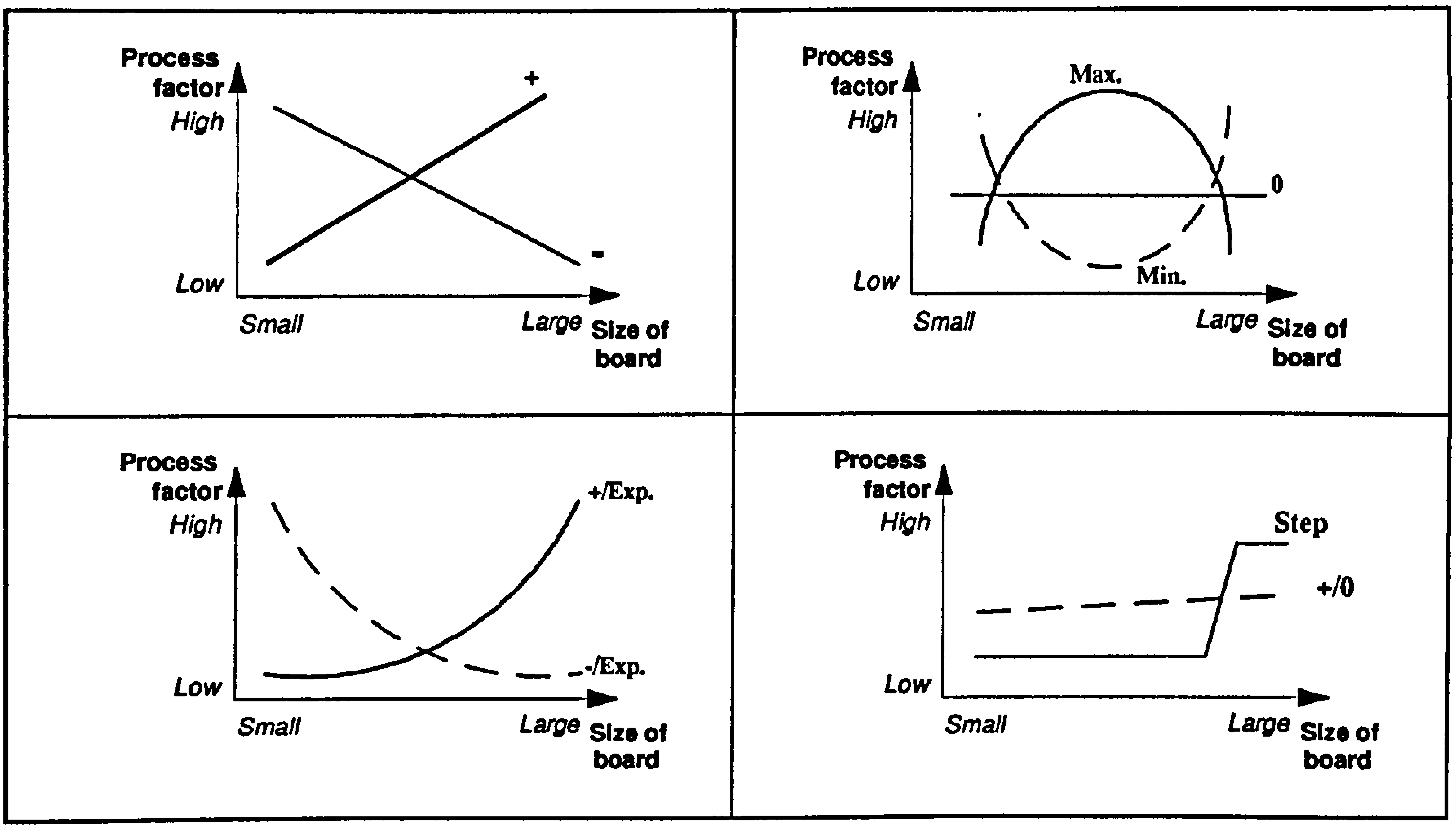


Figure A1 Classification of curve shapes for questionnaire survey

Of the questionnaires returned, the ICL and IBM responses were the most complete; these results are compiled into a comparative ranking table, as shown in table A2. The highlighted boxes represent responses that are not homogenous. Differences in opinion with regard to ecological impacts are well contrasted by rankings with at least a difference of 4 points between them. However, there are certain pairs of responses that are in close agreement, these are summarised in table A1. The ecological impact gradings in the last column are qualitatively assigned the following values: High (1-8), Medium (9-17) and Low (18-25) from earlier relative ranking values in table A2.

Process factors	Impact relationship with size	Ecological impact grading
Bareboard Manufacturing		
Dielectric consumption	Positive gradient effect	High
Resist consumption	Positive gradient effect	High
Copper consumption	No conclusive evidence	No conclusive evidence
Chemical cleaners consumption	No conclusive evidence	No conclusive evidence
Etchant consumption	No conclusive evidence	No conclusive evidence
Water consumption	Little or no effect	No conclusive evidence
Power consumption	No conclusive evidence	Medium
Raw material consumption	No conclusive evidence	High
Hazardous emissions	Positive gradient effect	No conclusive evidence
Waste management	Positive gradient effect	No conclusive evidence
Ease of clean manufacturing	No conclusive evidence	No conclusive evidence
PCB assembly		
Solder consumption	Positive gradient effect	High
Nickel/ Gold consumption	Positive gradient effect	Medium
Cost of plant	No conclusive evidence	No conclusive evidence
Ease of rework	No conclusive evidence	Low
Materials requiring special handling	No conclusive evidence	Low
Through-life phase		
Ease of serviceability	No conclusive evidence	No conclusive evidence
Ease of upgrade	No conclusive evidence	No conclusive evidence
Potential of product life extension	Little or no effect	Medium
Energy consumption	Positive gradient effect	No conclusive evidence
End-of-life phase		
Ease of disassembly	No conclusive evidence	No conclusive evidence
Ease of components recovery	No conclusive evidence	No conclusive evidence
Level of toxic substances	No conclusive evidence	High
Recycling potential without downgrade	No conclusive evidence	No conclusive evidence
Ease of disposal	Positive gradient effect	No conclusive evidence

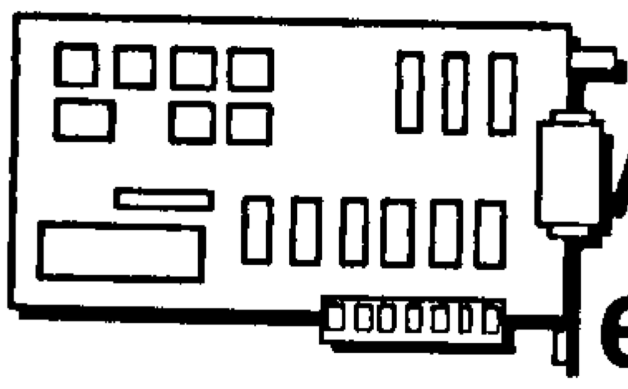
Table A1 Summary of survey results

Process factors	Impact relationship with size		Relative ranking of (A)		Relative ranking for (A)x(B)	
	ICL response	*IBM response*	*ICL response*	*IBM response*	*ICL response*	*IBM response*
Bareboard Manufacturing						
Dielectric consumption	+	+	1	1	1	1
Resist consumption	+	+	1	2	1	2
Copper consumption	Max.	+	22	2	20	2
Chemical cleaners consumption	Step	+	17	2	17	2
Etchant consumption	Step	+	13	2	13	2
Water consumption	0	+/0	21	2	20	2
Power consumption	0	+	11	13	11	13
Raw material consumption	+	+/Exp.	1	2	1	2
Hazardous emissions	+/0	+	15	2	15	2
Waste management	+/0	+	1	13	1	14
Ease of clean manufacturing	0	+	18	13	18	14
PCB Assembly						
Solder consumption	+	+	1	2	1	2
Nickel/ Gold consumption	+/0	+	14	13	14	14
Cost of plant	Step	+	18	13	18	14
Ease of rework	Step	Min.	20	23	22	24
Materials requiring special handling	+	0	23	22	23	23
Through-life phase						
Ease of serviceability	Max.	Min.	-	24	-	25
Ease of upgrade	0	+	24	2	23	2
Potential of product life extension	Max.	-	12	13	12	14
Energy consumption	+	+	15	2	15	2
End-Of-Life Phase						
Ease of disassembly	0	Min.	1	20	1	20
Ease of components recovery	Step	-/Exp.	1	20	1	21
Level of toxic substances	+	+	1	2	1	2
Recycling potential without downgrade	0	0	1	2	1	22
Ease of disposal	+/0	+	1	13	1	14

Table A2 Table of comparative rankings

Process factors	Impact relationship with size	Ranking for ecological impact (A)	Relative ranking of (A)	Level of confidence (B)	Multiplied rating (A) x (B)	Relative ranking for (A)x(B)
Bareboard Manufacturing						
Dielectric consumption	+	10	1	5	50	1
Resist consumption	+	10	1	5	50	1
Copper consumption	Max.	2	22	5	10	20
Chemical cleaners consumption	Step	4	17	5	20	17
Etchant consumption	Step	7	13	5	35	13
Water consumption	0	2	21	5	10	20
Power consumption	0	9	11	5	45	11
Raw material consumption	+	10	1	5	50	1
Hazardous emissions	+/0	5	15	5	25	15
Waste management	+/0	10	1	5	50	1
Ease of clean manufacturing	0	3	18	5	15	18
PCB Assembly						
Solder consumption	+	10	1	5	50	1
Nickel/ Gold consumption	+/0	6	14	5	30	14
Cost of plant	Step	3	18	5	15	18
Ease of rework	Step	2	20	3	6	22
Materials requiring special handling	+	1	23	5	5	23
Through-life phase						
Ease of serviceability	Max.	?	-	?	?	-
Ease of upgrade	0	1	24	5	5	23
Potential of product life extension	Max.	8	12	5	40	12
Energy consumption	+	5	15	5	25	15
End-Of-Life Phase						
Ease of disassembly	0	10	1	5	50	1
Ease of components recovery	Step	10	1	5	50	1
Level of toxic substances	+	10	1	5	50	1
Recycling potential without downgrade	0	10	1	5	50	1
Ease of disposal	+/0	10	1	5	50	1

Table A3 Summary of survey response from ICL



A survey of miniaturisation and its ecological impact in PCBs

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How to complete the questionnaire...

This survey consists of three sections which examines the effects of varying **Board sizes** versus:

- **Bareboard Manufacturing**
- **PCB assembly**
- **Through-life** and
- **End-of-Life** phases in the life cycle of a PCB.

For each process factor examined, please grade its ecological impact on a scale of 1 to 10 where applicable: **1 (negligible impact) - 10 (strongest impact)** and circle the level of confidence: **1 (least confident) - 5 (most confident).** In addition, please select the approximate board size relationship by circling the corresponding graph number from **Column A.**

Alternatively, you may sketch your own graphical relationship within the labelled axes provided on the right hand box. A short annotation of your graph is greatly appreciated!

A completed sample is shown on the following page.

Your particulars below will be used for filing purposes only:

NAME: Phil Hamilton

NAME OF COMPANY/ INSTITUTION: ICL D2D

ADDRESS: Kidsgrove, Stoke on Trent

TELEPHONE:

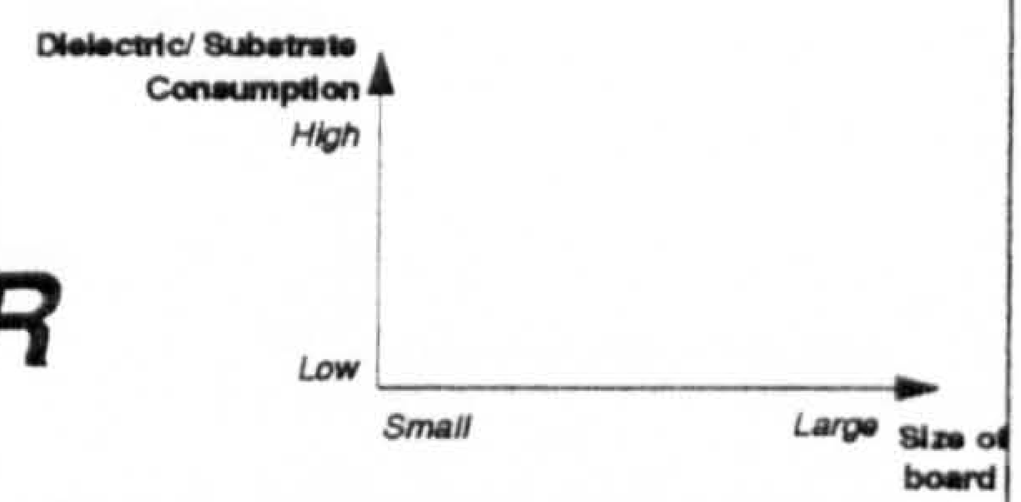
PLEASE COMPLETE AND RETURN.

Thank you very much for spending time to complete this questionnaire, your contribution will be of invaluable help to my research! If you do require further clarification, please do not hesitate to contact me at Tel: +44-1509-228251. The completed questionnaire may be returned to me by either mail or fax: (Mr. MK Low, Dept. of Manufacturing, Loughborough University, Loughborough, Leics., LE11 3TU, England, UK Fax: +44-1509-267725)

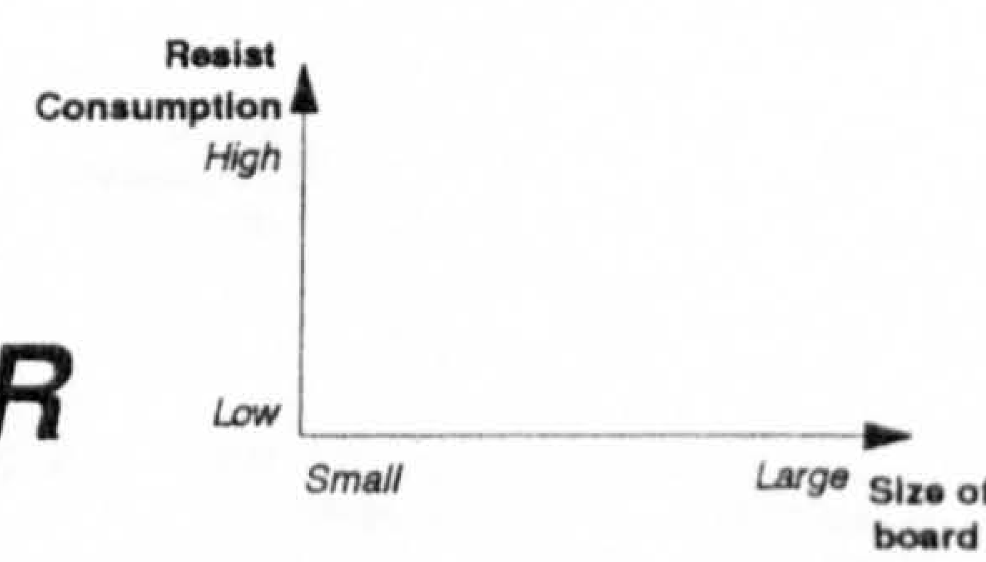
Please turn over ☞

SECTION A Bareboard Manufacturing

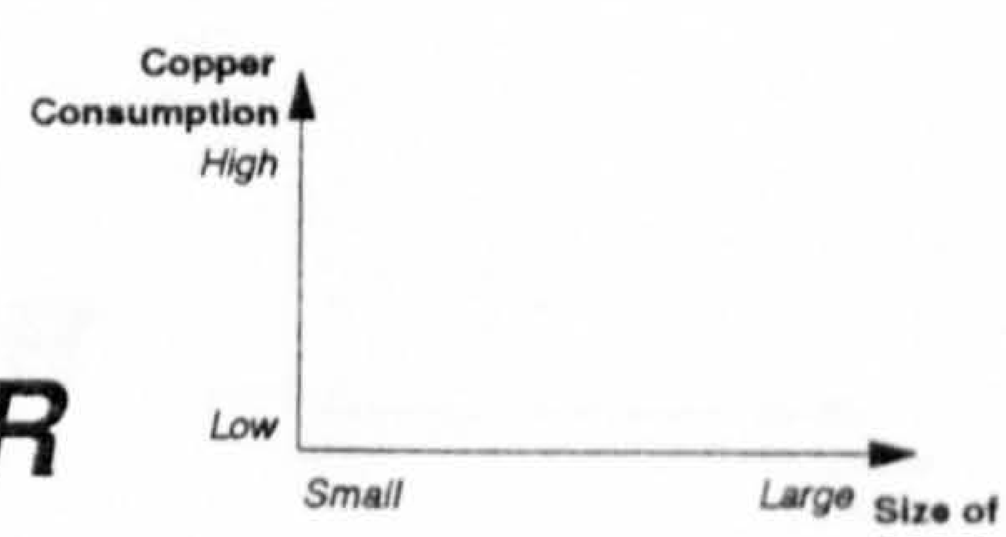
Dielectric/ Substrate consumption vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 *You may wish to annotate your graph with a comment at the foot of the page.*

Resist consumption vs. Size of board

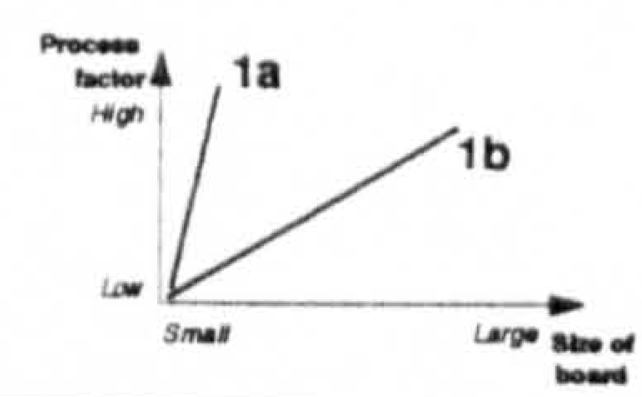
Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 *You may wish to annotate your graph with a comment at the foot of the page.*

Copper consumption vs. Size of board

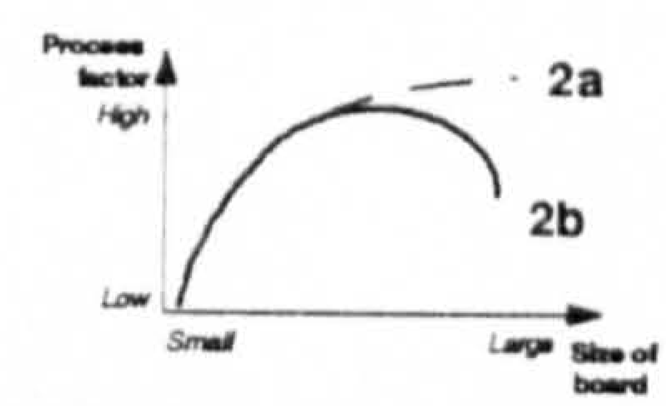
Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 *You may wish to annotate your graph with a comment at the foot of the page.*

Column A

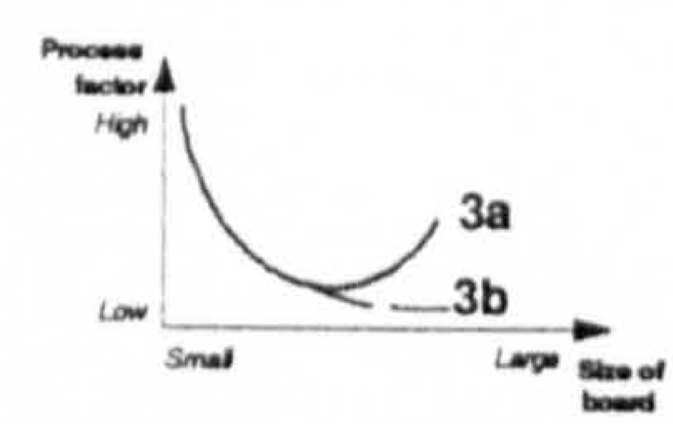
Graph 1



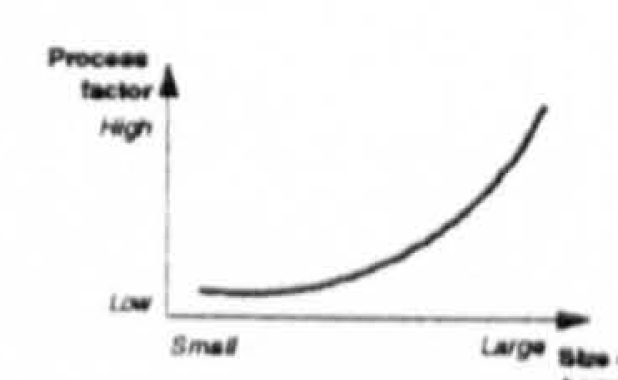
Graph 2



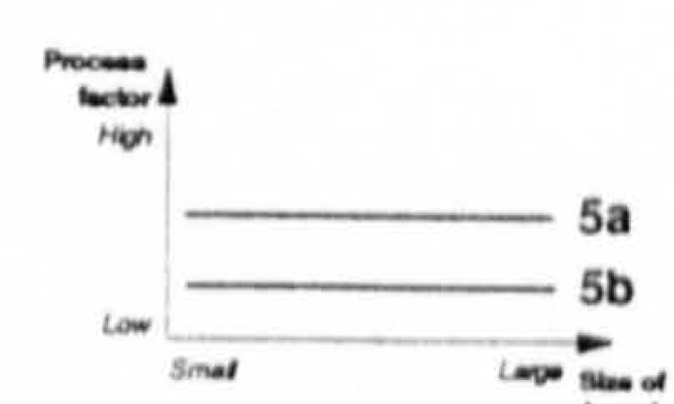
Graph 3



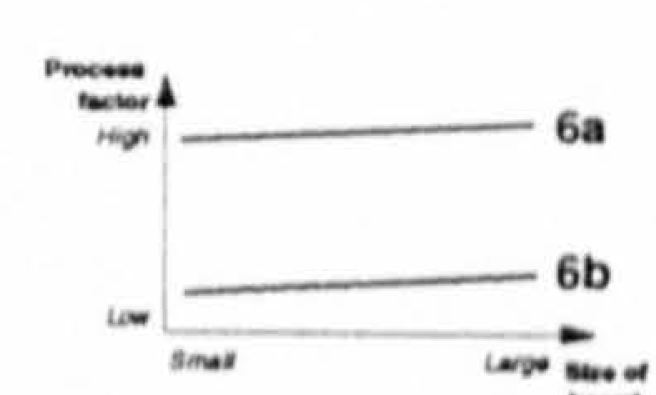
Graph 4



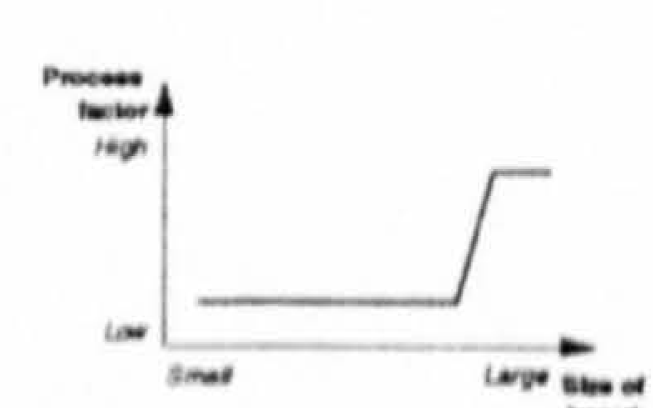
Graph 5



Graph 6



Graph 7



***Remarks/ Annotations for graphs*:**

Bareboard Manufacturing (continued)

Environmentally friendly!

Chemical cleaners consumption vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

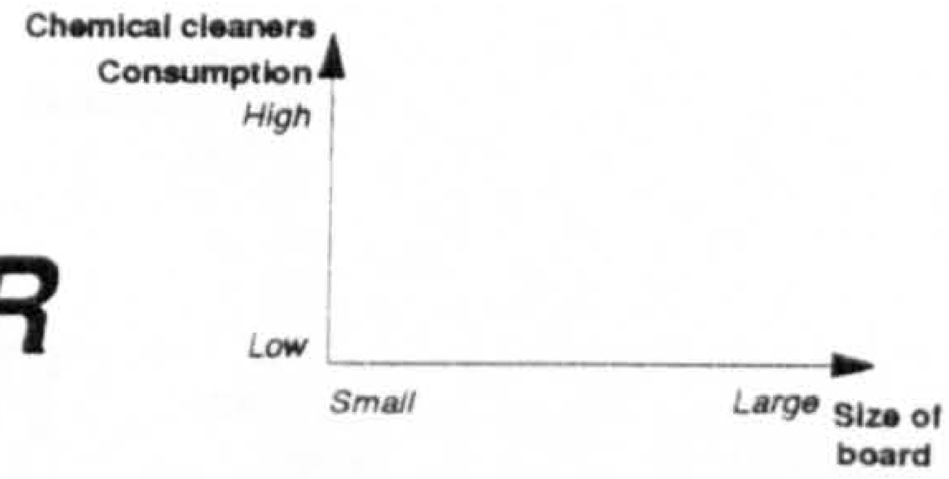
1 2 3 4 5

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship



**You may wish to annotate your graph with a comment at the foot of the page.*

Etchant consumption vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

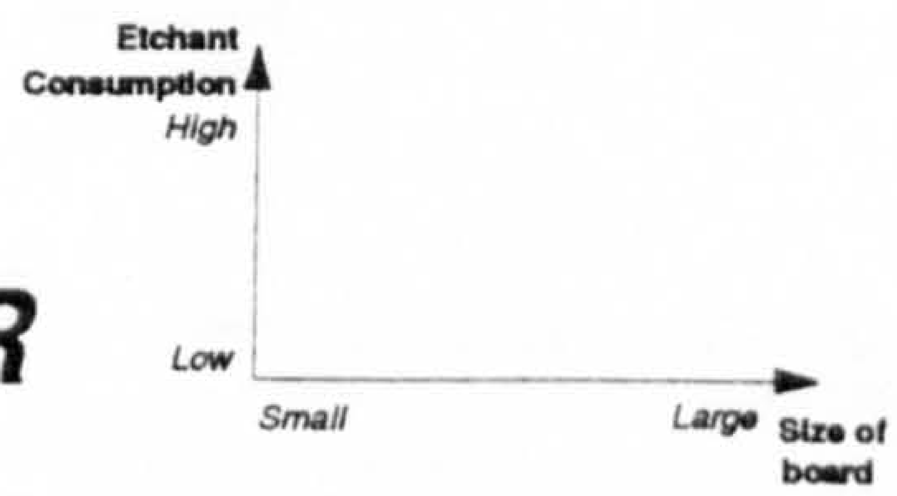
1 2 3 4 5

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship:



**You may wish to annotate your graph with a comment at the foot of the page.*

Water consumption vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

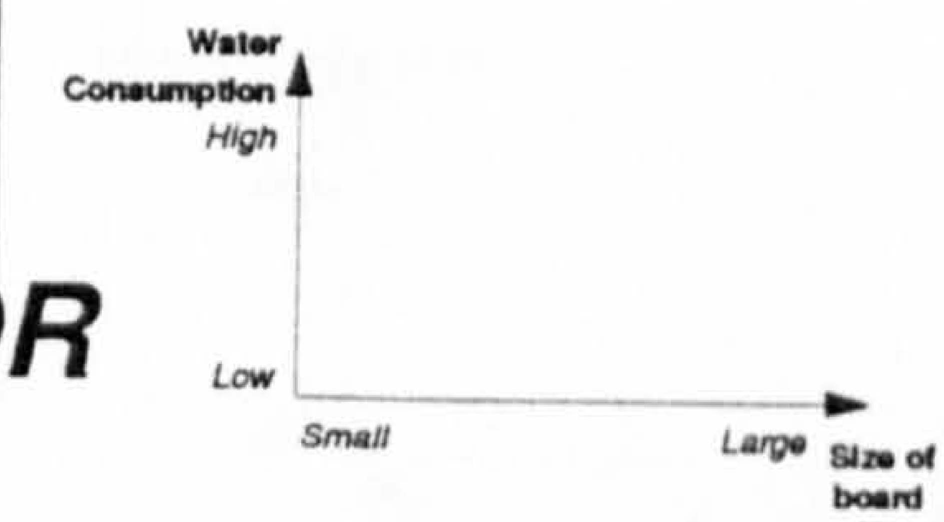
1 2 3 4 5

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

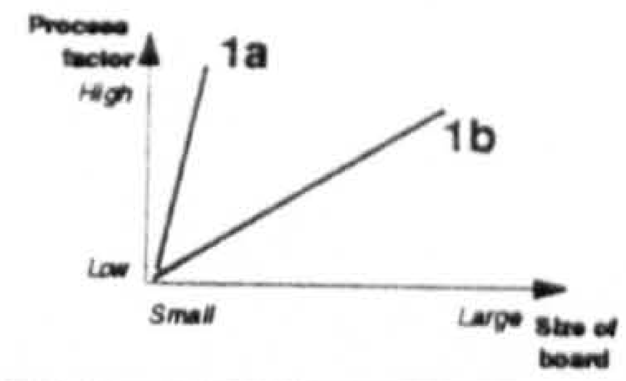
Sketch ***own*** graphical relationship:



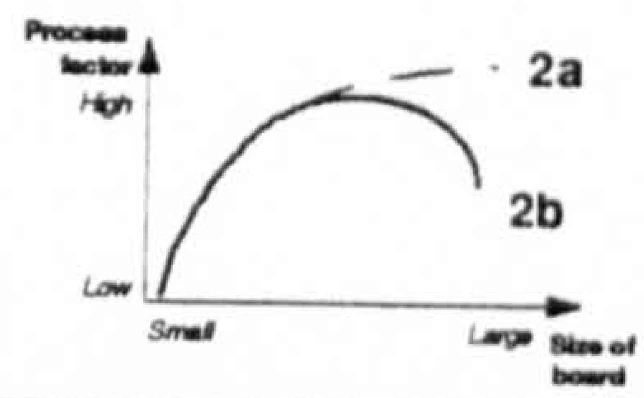
**You may wish to annotate your graph with a comment at the foot of the page.*

Column A

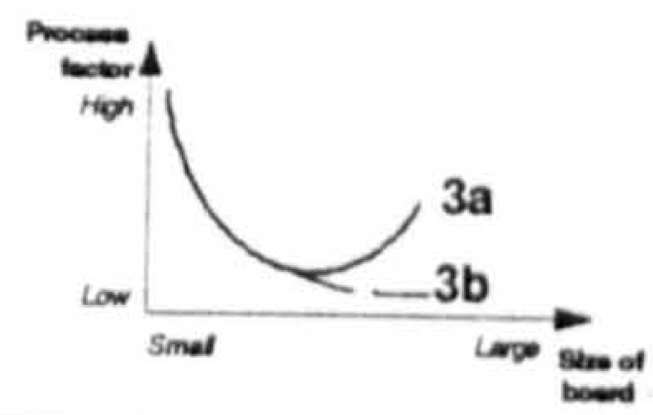
Graph 1



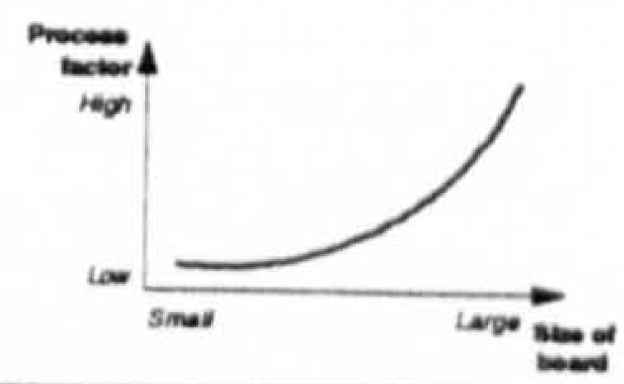
Graph 2



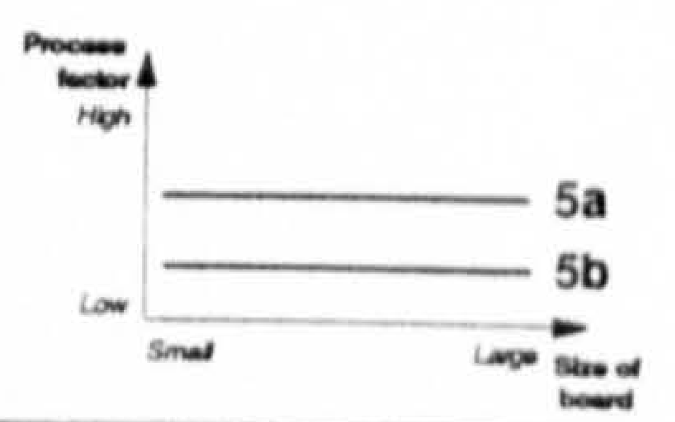
Graph 3



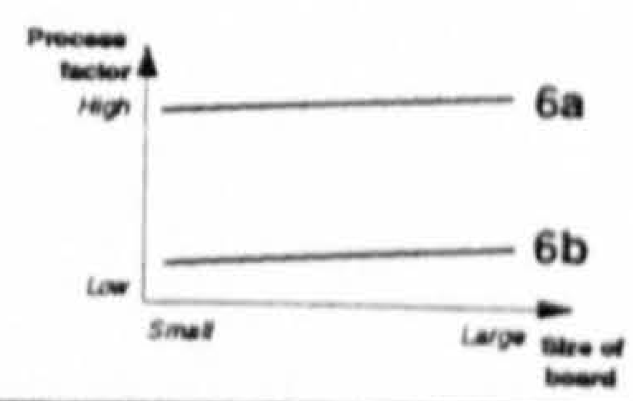
Graph 4



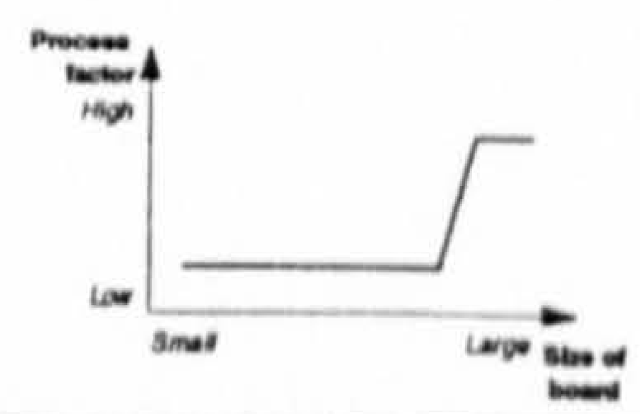
Graph 5



Graph 6



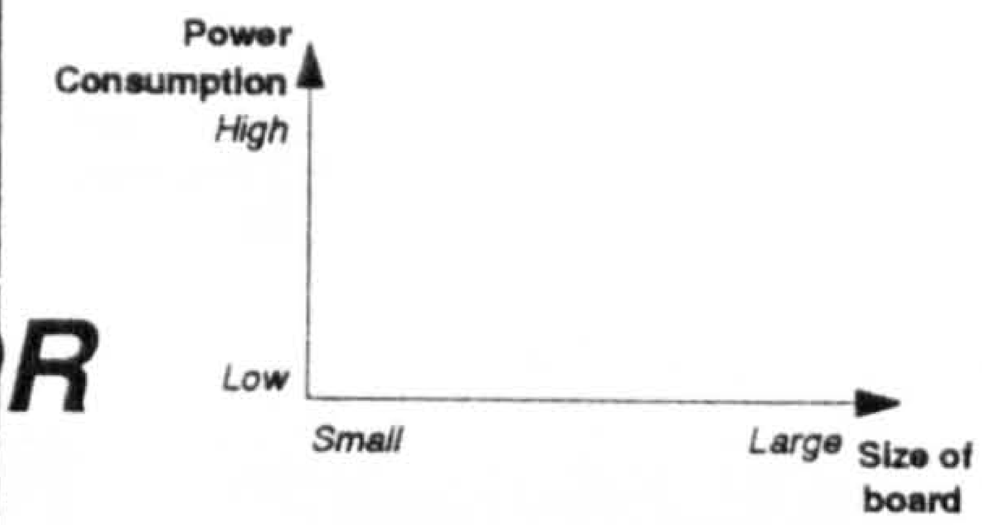
Graph 7



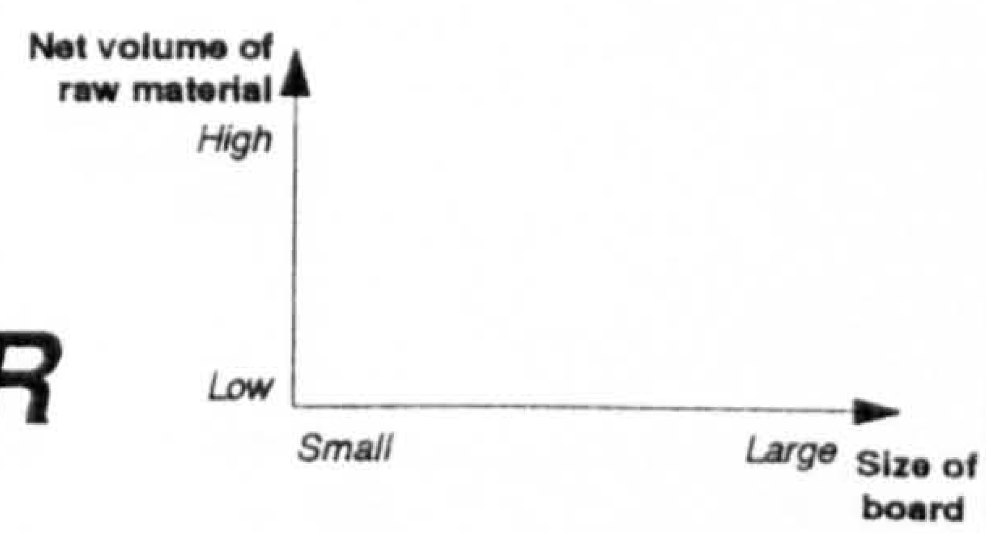
Remarks/ Annotations for graphs:

Bareboard Manufacturing (continued)

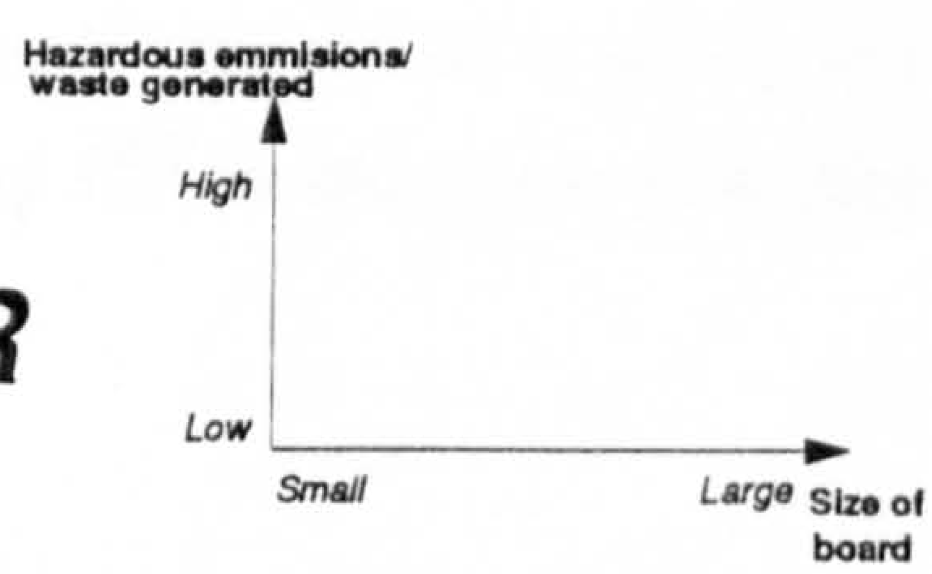
Power consumption vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 **You may wish to annotate your graph with a comment at the foot of the page.*

Net volume of raw materials vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 **You may wish to annotate your graph with a comment at the foot of the page.*

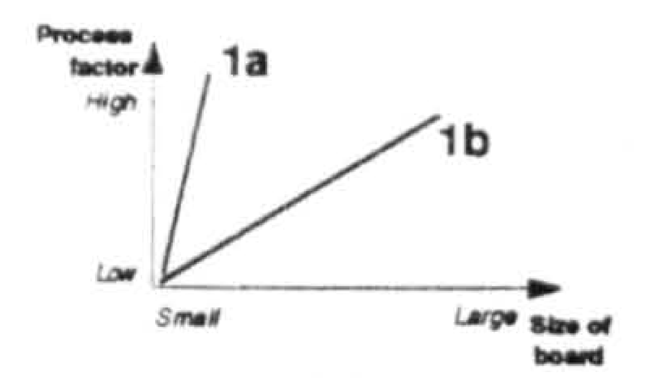
Level of hazardous emissions and waste generated vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**	 **You may wish to annotate your graph with a comment at the foot of the page.*

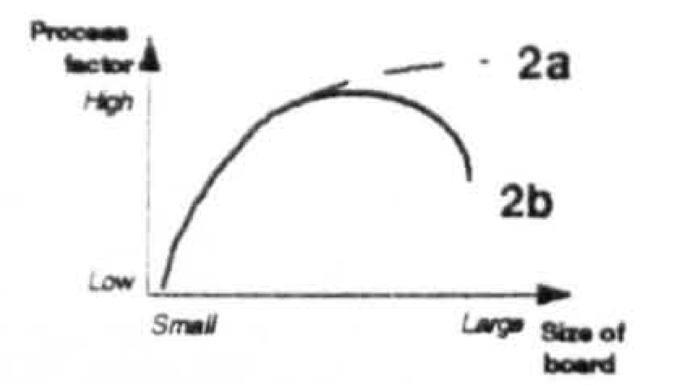
***Remarks/ Annotations for graphs*:**

Column A

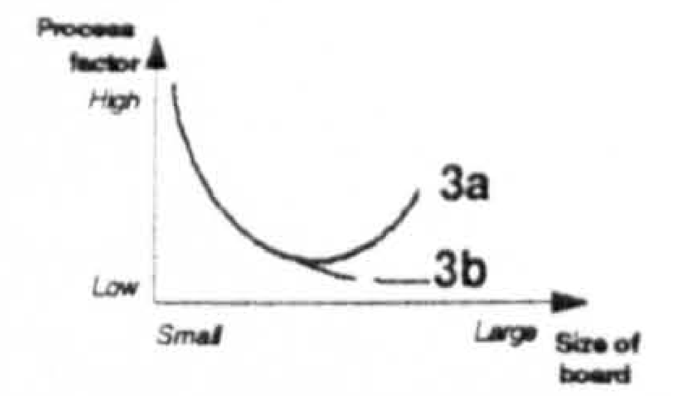
Graph 1



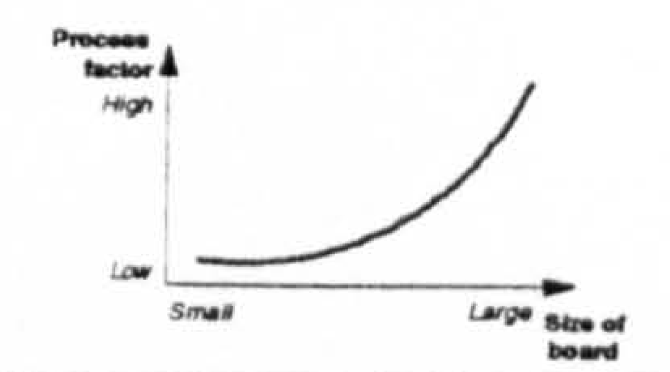
Graph 2



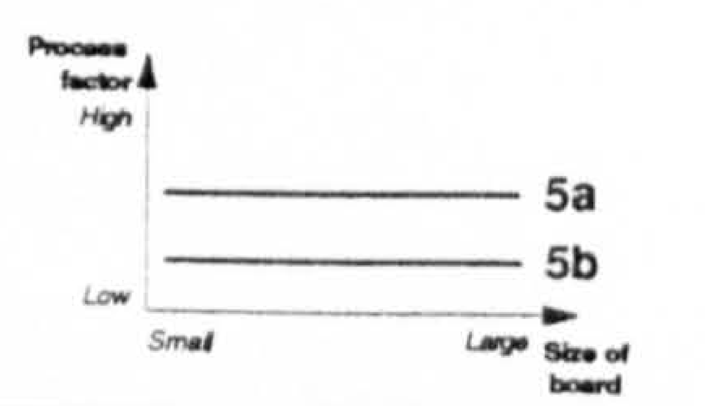
Graph 3



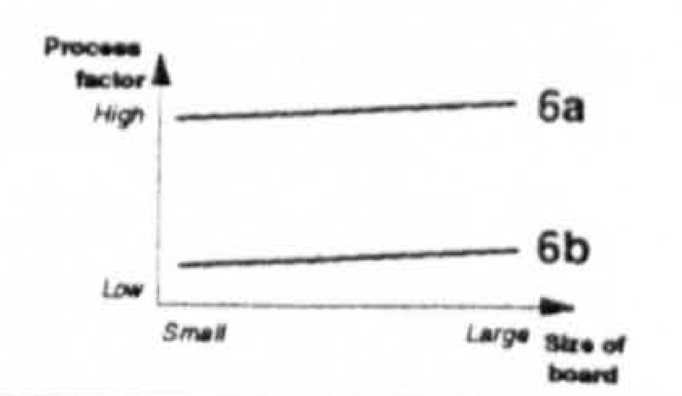
Graph 4



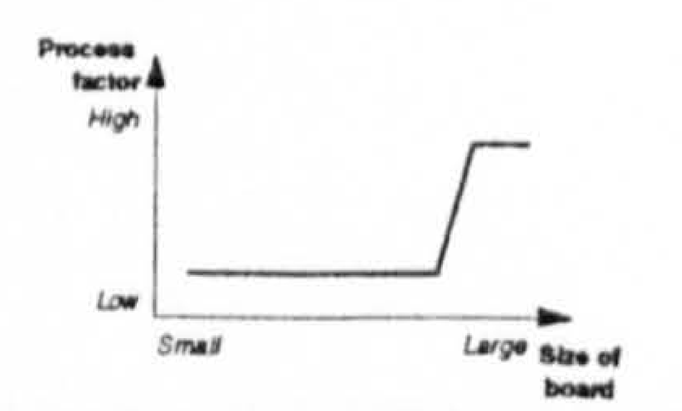
Graph 5



Graph 6

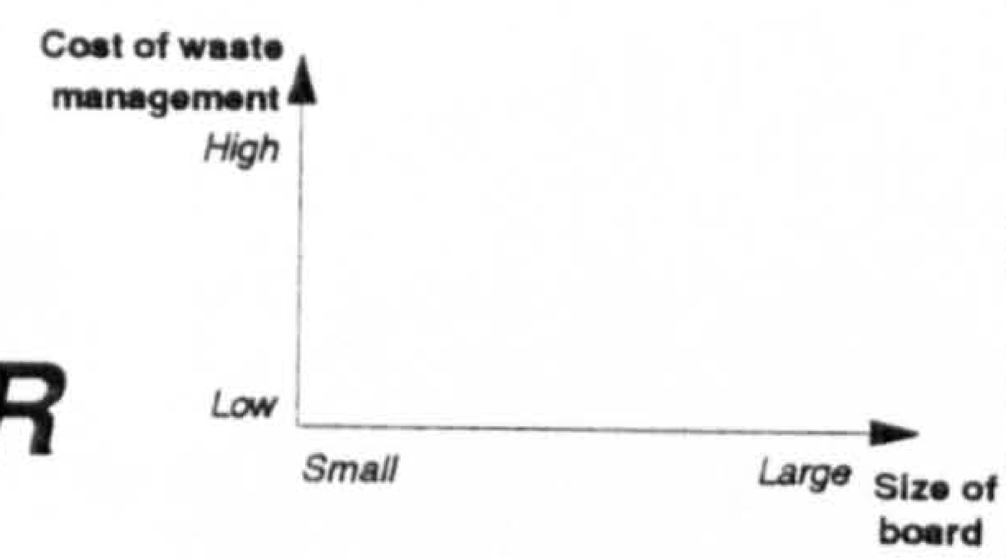


Graph 7

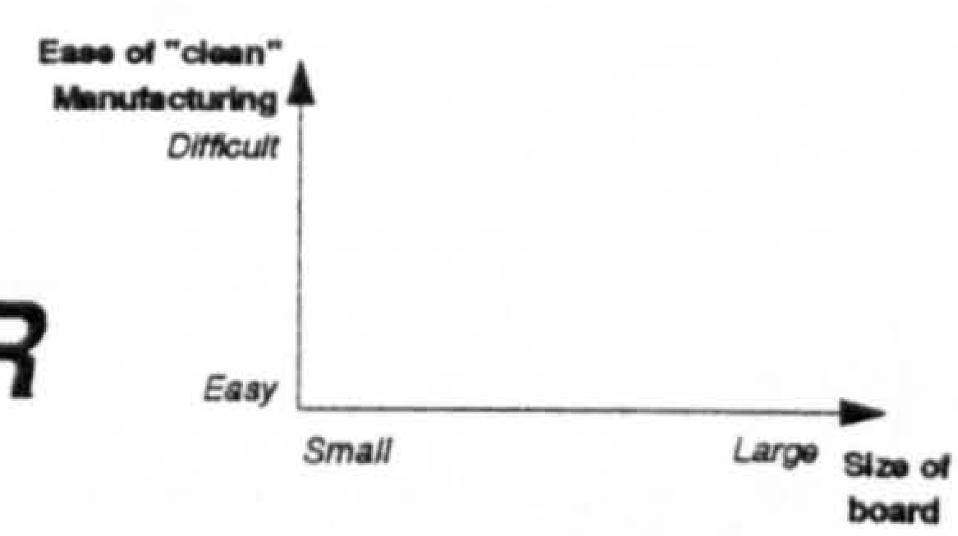


Bareboard Manufacturing (continued)

Cost of waste management vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:*	Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 (10) Level of confidence 1 2 3 4 (5)	1a 1b 2a 2b 3a 3b 4 5a 5b 6a (6b) 7	**OR**  *You may wish to annotate your graph with a comment at the foot of the page.*

Ease of "clean" manufacturing vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:*	Sketch ***own*** graphical relationship:
1 2 (3) 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 (5)	1a 1b 2a 2b 3a 3b 4 (5a) 5b 6a 6b 7	**OR**  *You may wish to annotate your graph with a comment at the foot of the page.*

Are there any significant changes likely to occur in the (near) future of bareboard manufacturing that will have significant impact on the ecological aspects of such products (i.e. technological breakthrough, etc.)?

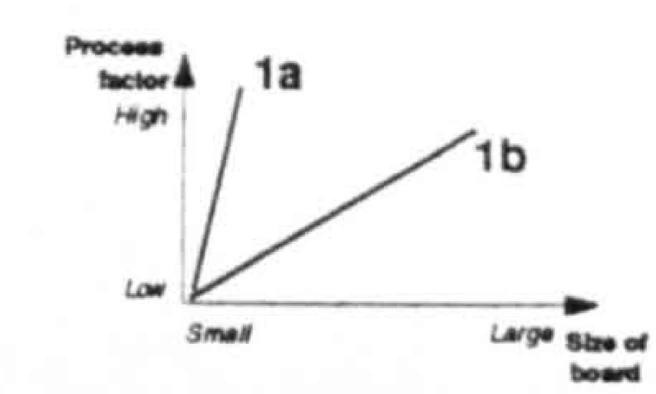
EU legislation on flame retardant compounds will necessitate a whole new range of materials hence my confidence range of (5) in the above (not just a fancy!)

Annotations for graphs/ other observations:

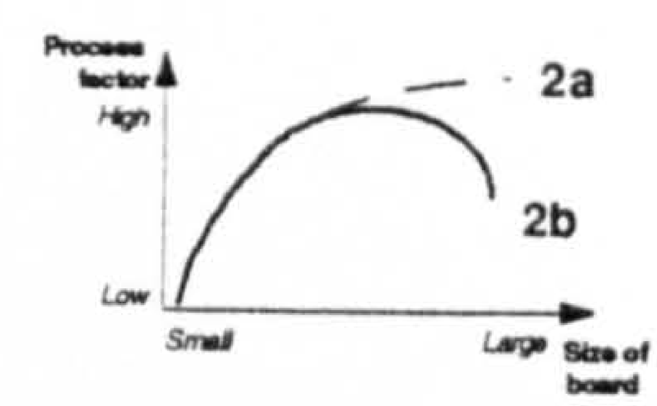
Water based process versus solvent process with an added hydrogen molecule MUST be forced onto the industry legislation.

Column A

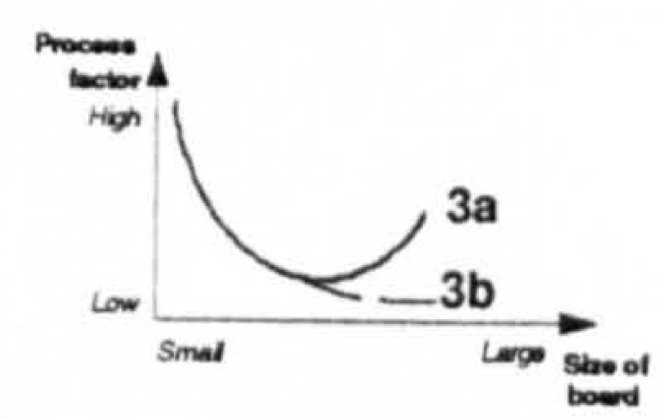
Graph 1



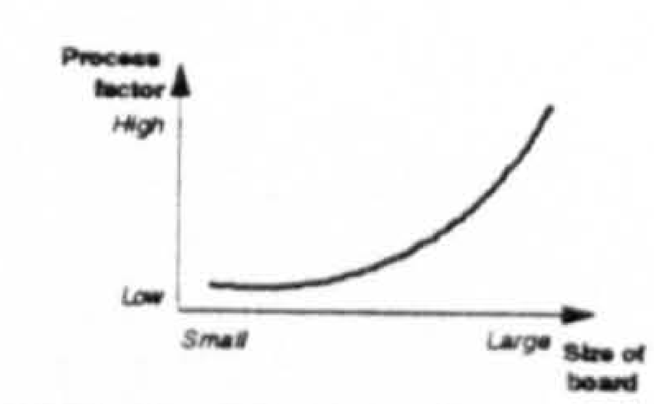
Graph 2



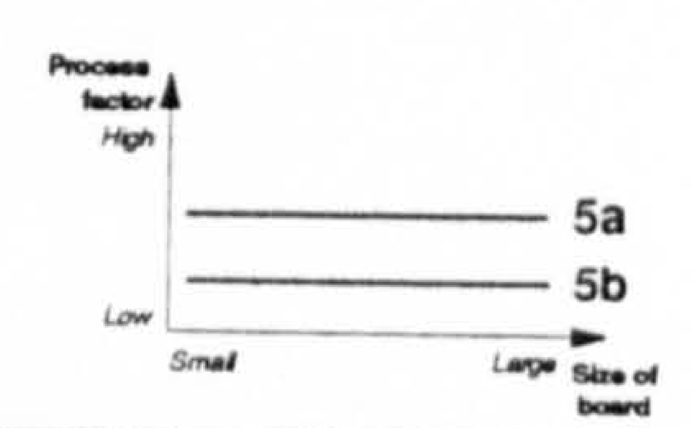
Graph 3



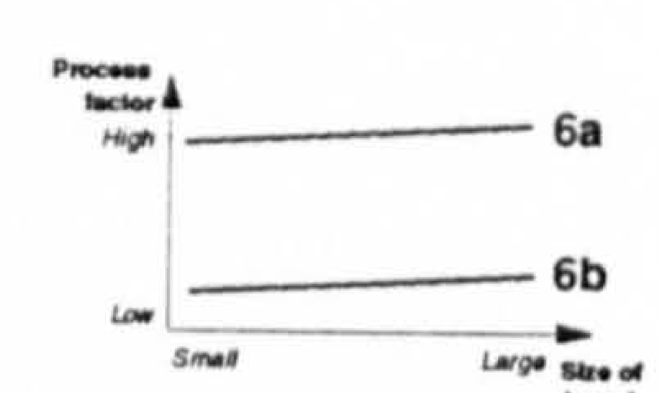
Graph 4



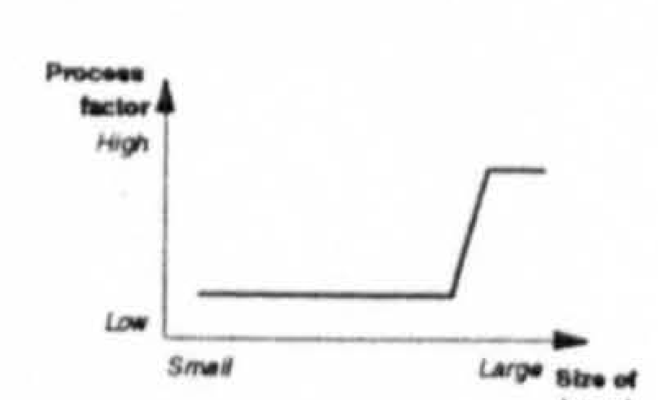
Graph 5



Graph 6



Graph 7



SECTION B PCB Assembly

Solder (Tin/ Lead) consumption vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

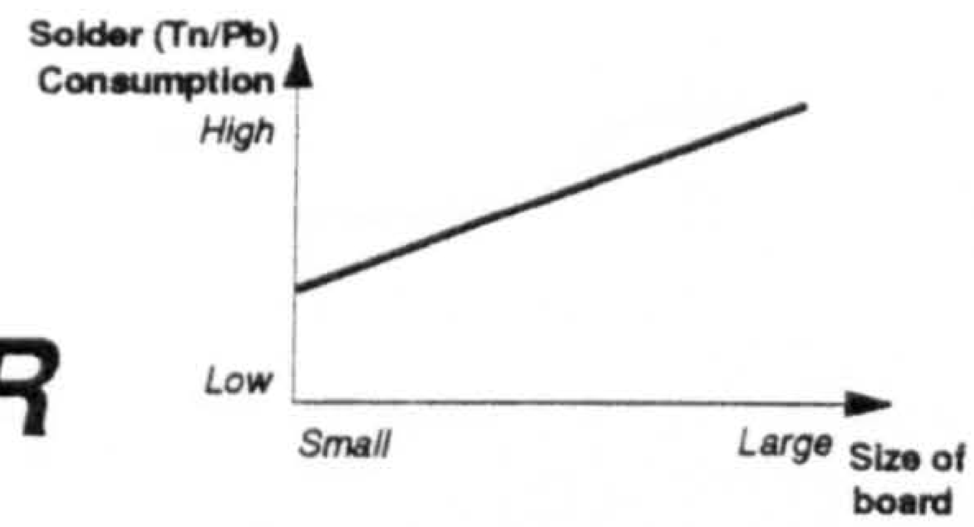
1 2 3 4 5

Approximate relationship with Size of Board.
Select graph from ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship:



**You may wish to annotate your graph with a comment at the foot of the page.*

Nickel/ Gold consumption vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

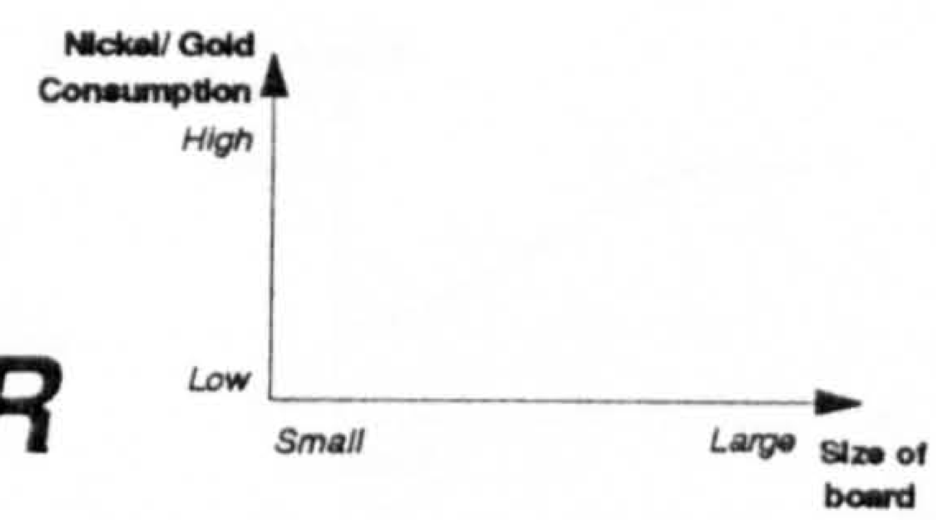
1 2 3 4 5

Approximate relationship with Size of Board.
Select graph from ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship:



**You may wish to annotate your graph with a comment at the foot of the page.*

Cost of plant/ Equipment vs. Size of board

Ranking for ecological impact

1 2 3 4 5

6 7 8 9 10

Level of confidence

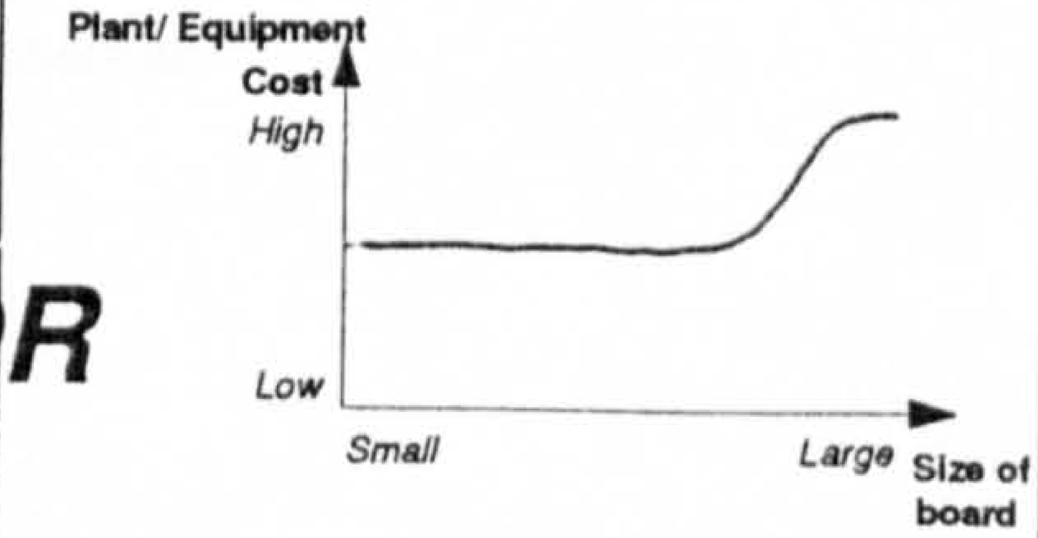
1 2 3 4 5

Approximate relationship with Size of Board.
Select graph from ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

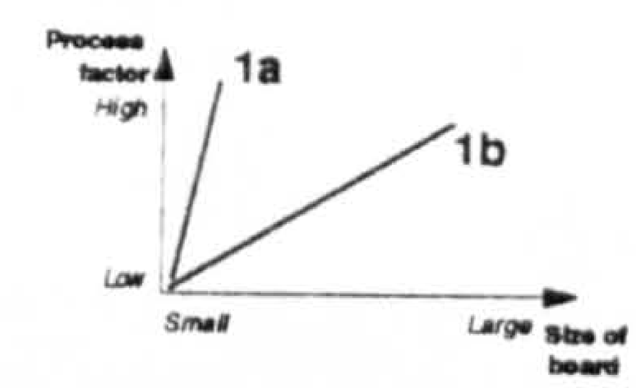
Sketch ***own*** graphical relationship:



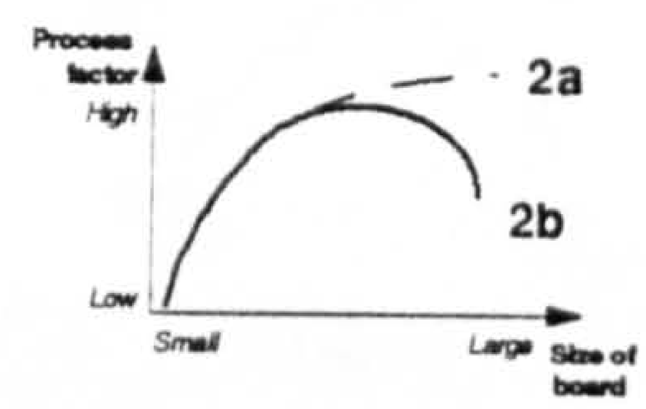
**You may wish to annotate your graph with a comment at the foot of the page.*

Column A

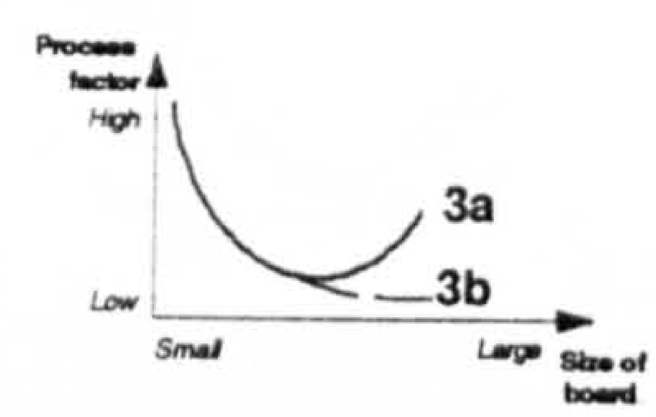
Graph 1



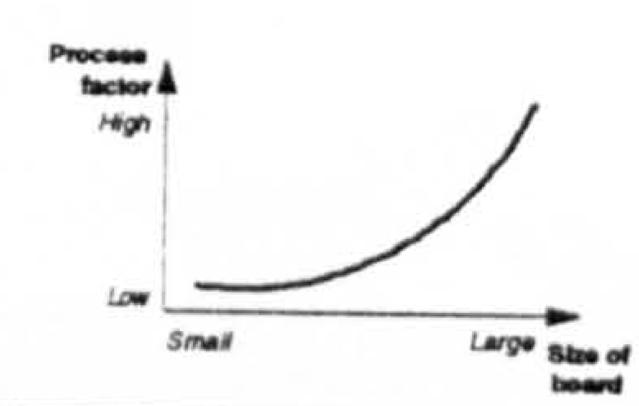
Graph 2



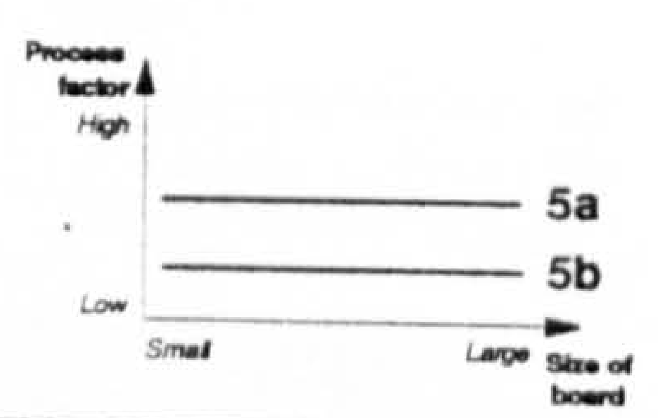
Graph 3



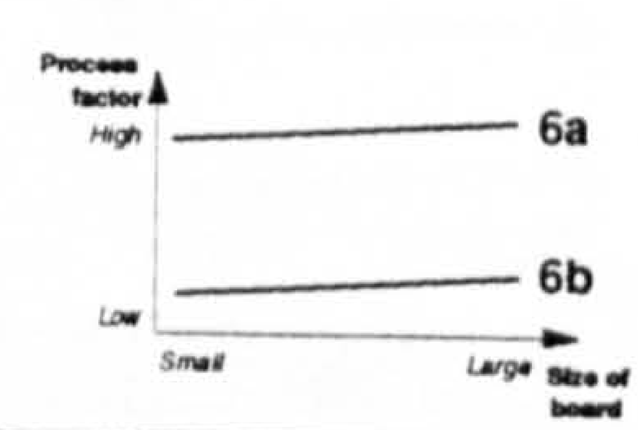
Graph 4



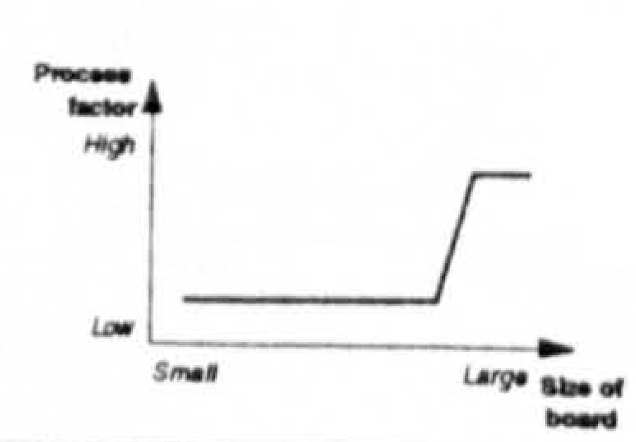
Graph 5



Graph 6



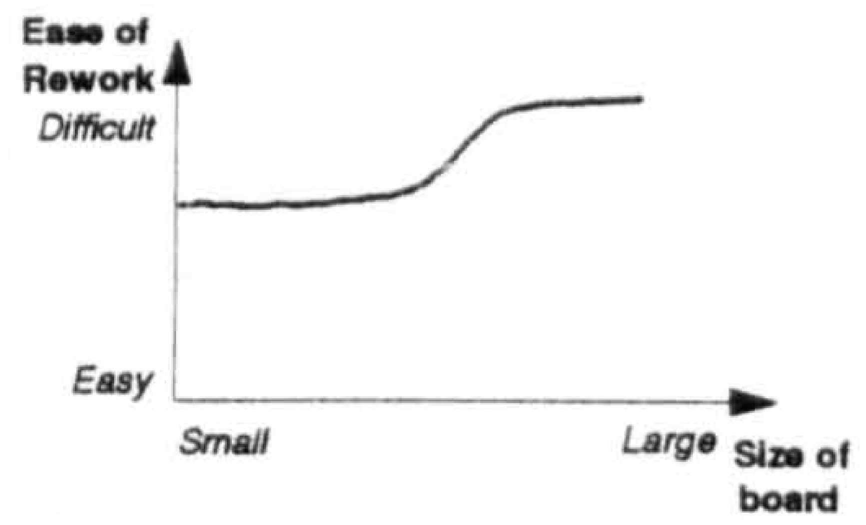
Graph 7



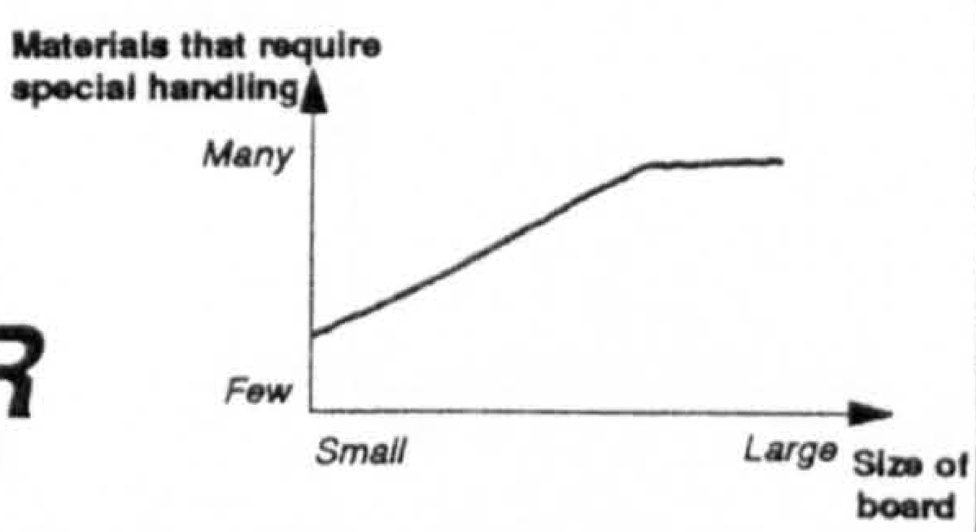
Remarks/ Annotations for graphs:

PCB Assembly (continued)

Ease of rework vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*	Sketch ***own*** graphical relationship:
1 (2) 3 4 5 6 7 8 9 10 Level of confidence 1 2 (3) 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**  *You may wish to annotate your graph with a comment at the foot of the page.*

Materials that require special handling vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*	Sketch ***own*** graphical relationship:
(1) 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 (5)	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**  *You may wish to annotate your graph with a comment at the foot of the page.*

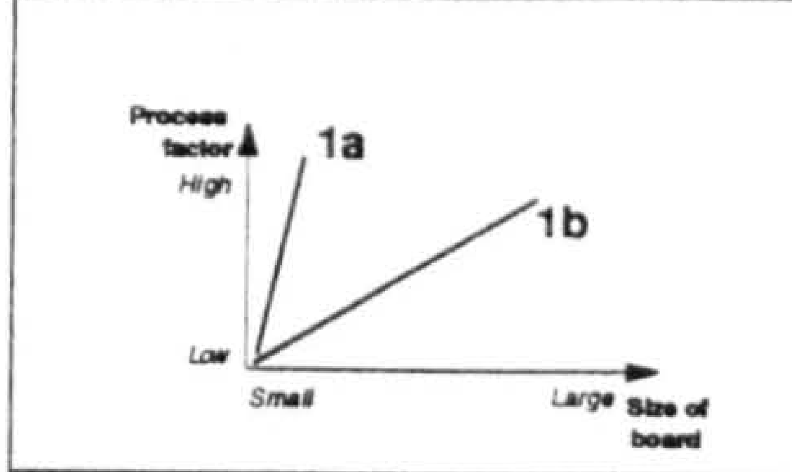
Are there any significant changes likely to occur in the (near) future of PCB assembly that will have significant impact on the ecological aspects of such products?

A move from glass enforcement to thin polymer supporting materials will impact on the end of life reclamation management.

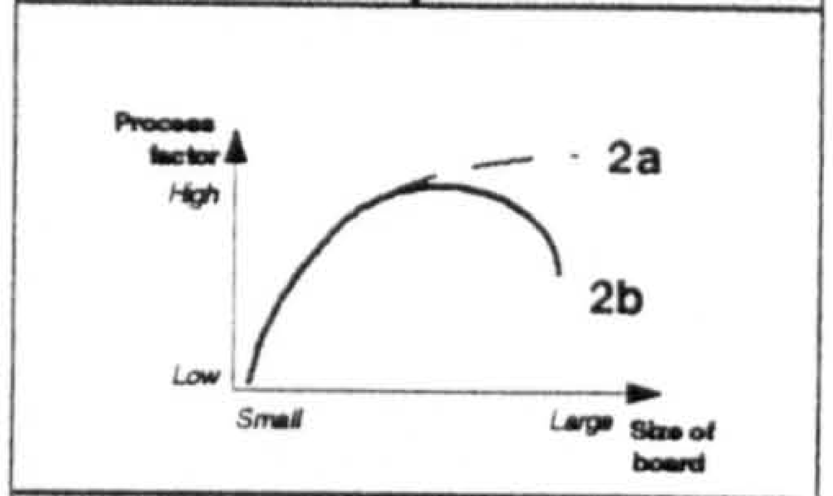
Annotations for graphs/ other observations:

Column A

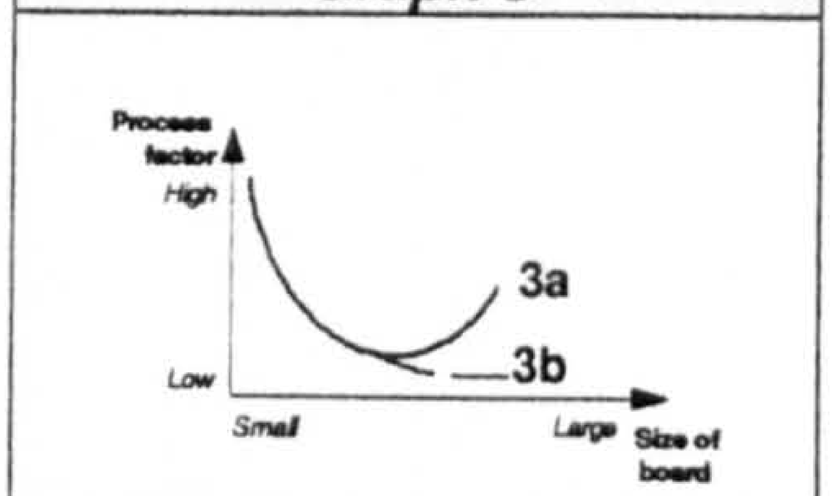
Graph 1



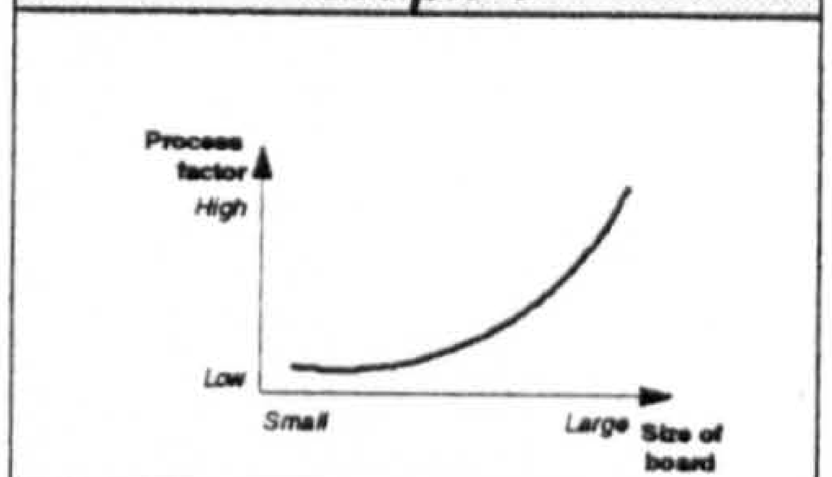
Graph 2



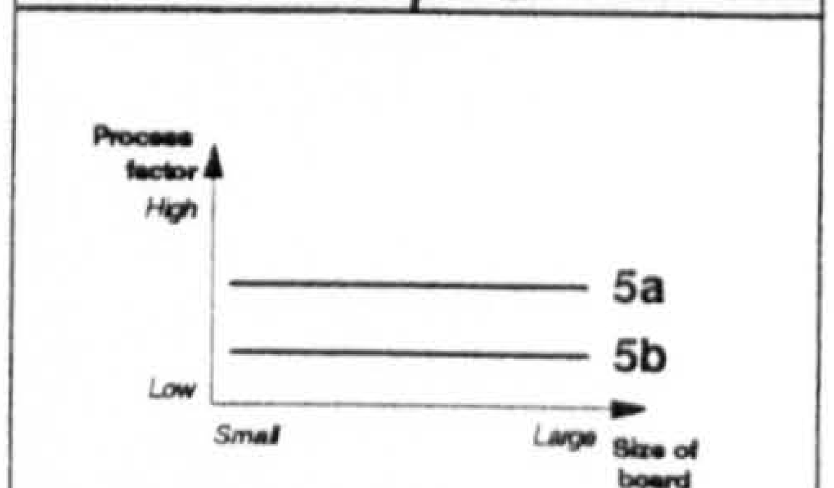
Graph 3



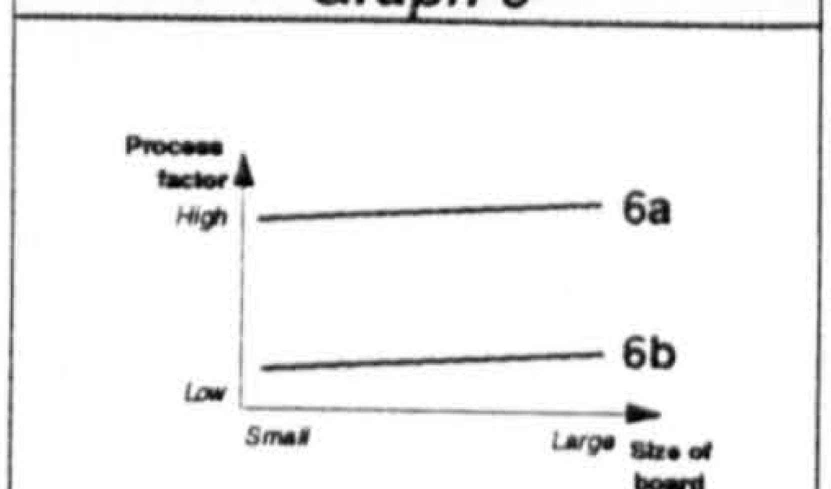
Graph 4



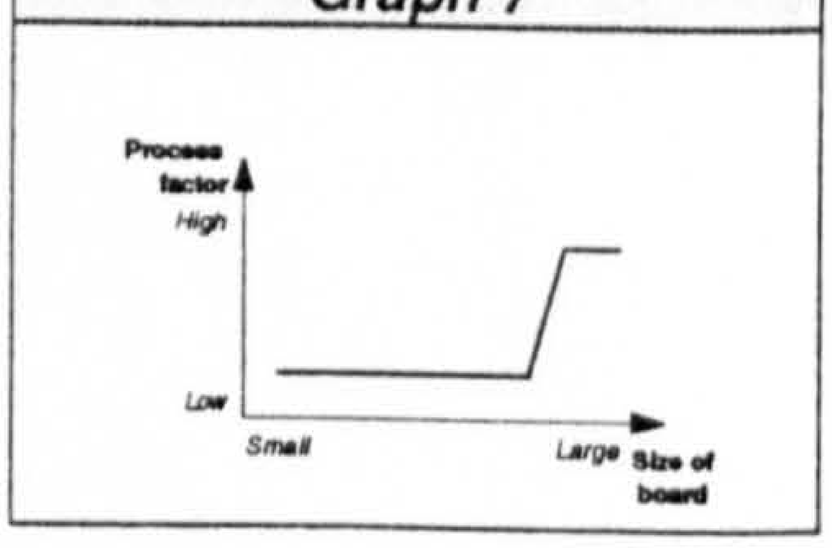
Graph 5



Graph 6

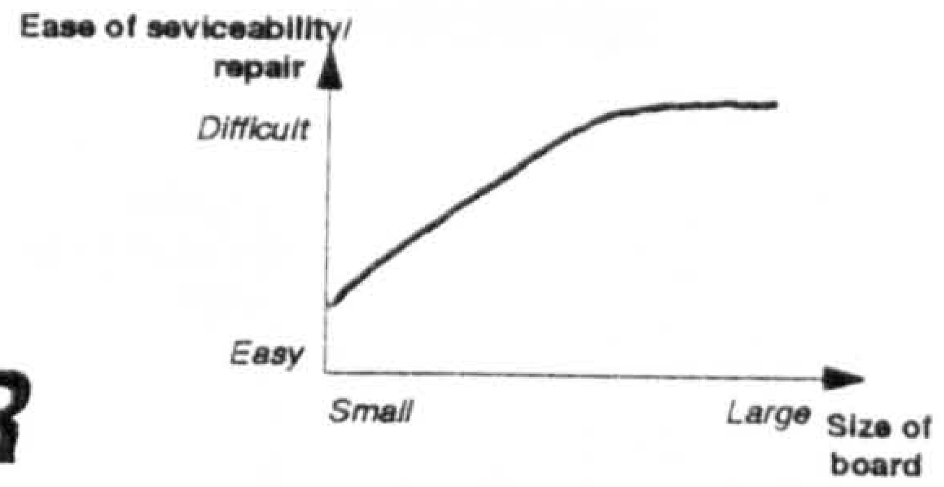


Graph 7

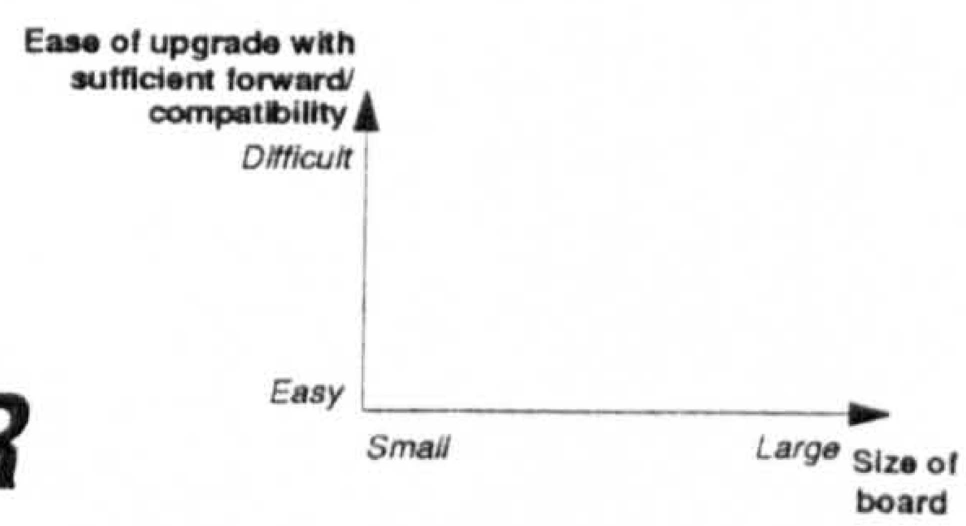


SECTION C Through-life phase

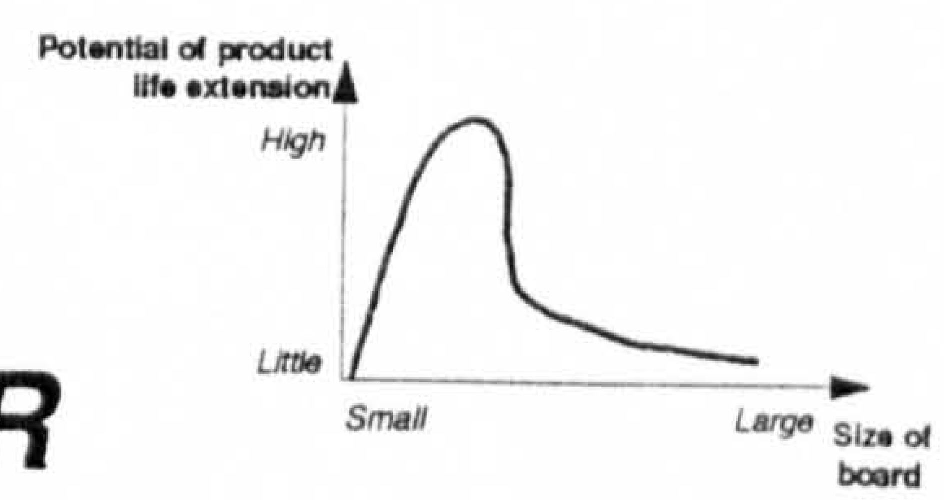
Ease of serviceability vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*	Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**  **You may wish to annotate your graph with a comment at the foot of the page.*

Ease of upgrade with sufficient forward/ backward compatibility vs. Size of board

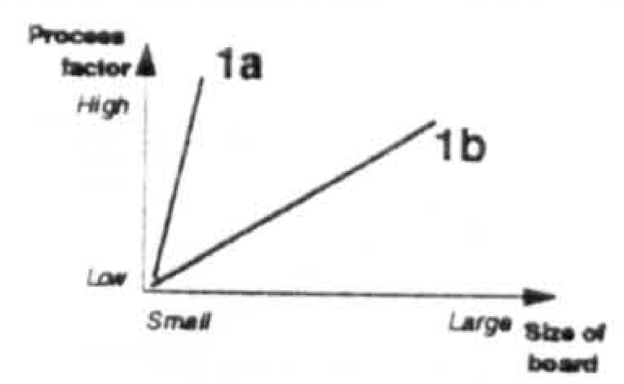
Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*	Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**  **You may wish to annotate your graph with a comment at the foot of the page.*

Potential of product life extension vs. Size of board

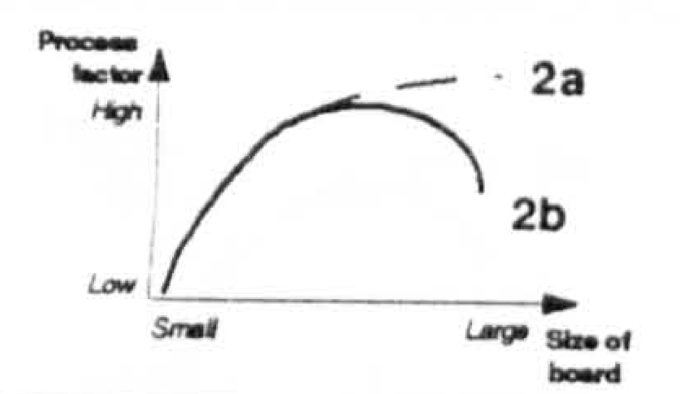
Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*	Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 10 Level of confidence 1 2 3 4 5	1a 1b 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR**  **You may wish to annotate your graph with a comment at the foot of the page.*

Column A

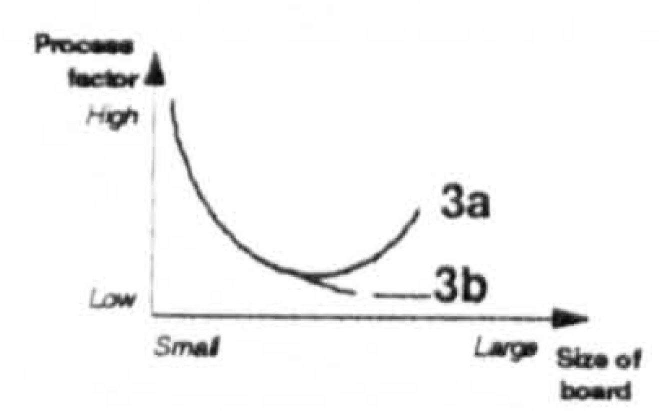
Graph 1



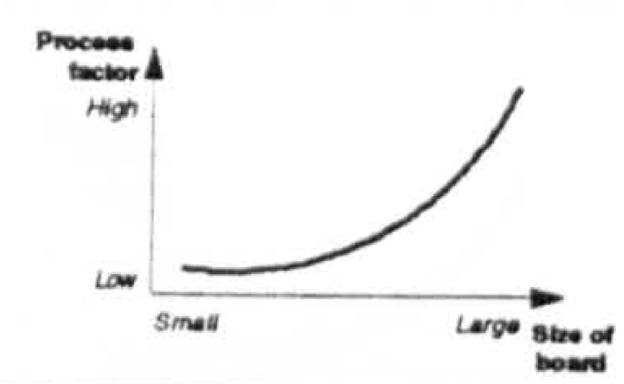
Graph 2



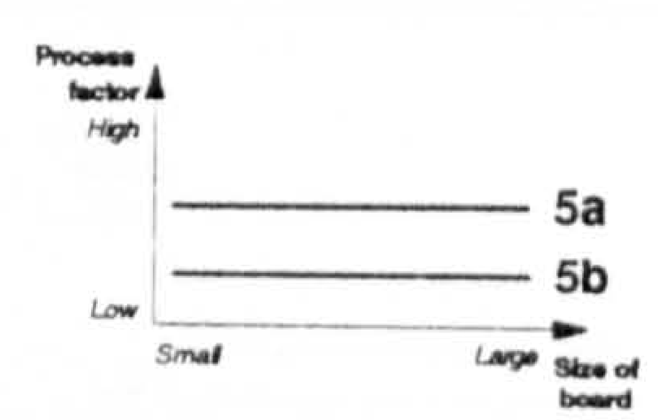
Graph 3



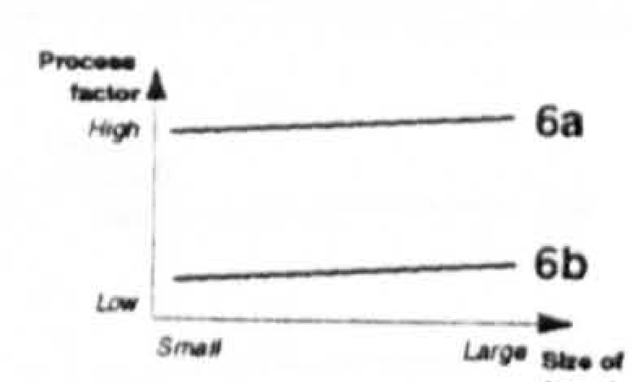
Graph 4



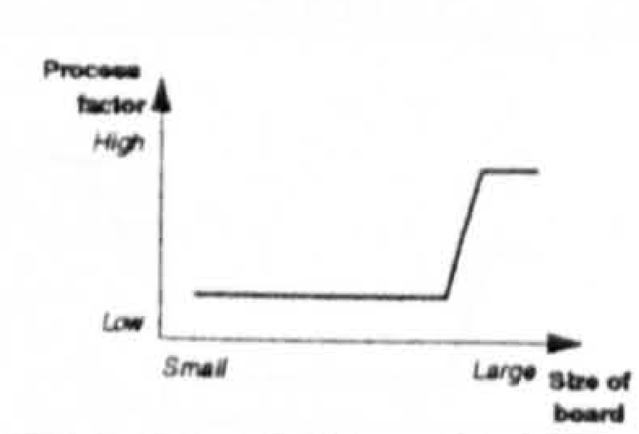
Graph 5



Graph 6

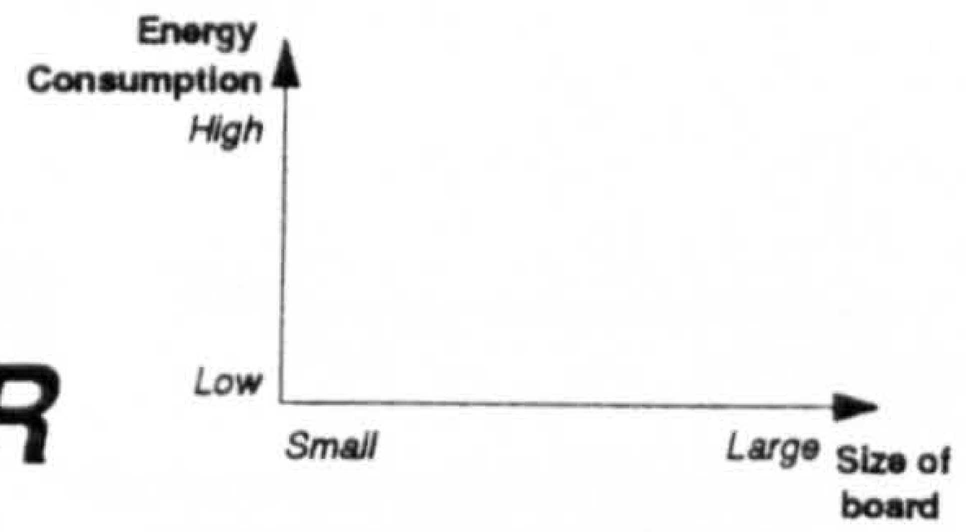


Graph 7



Remarks/ Annotations for graphs:

Through-life phase (continued)

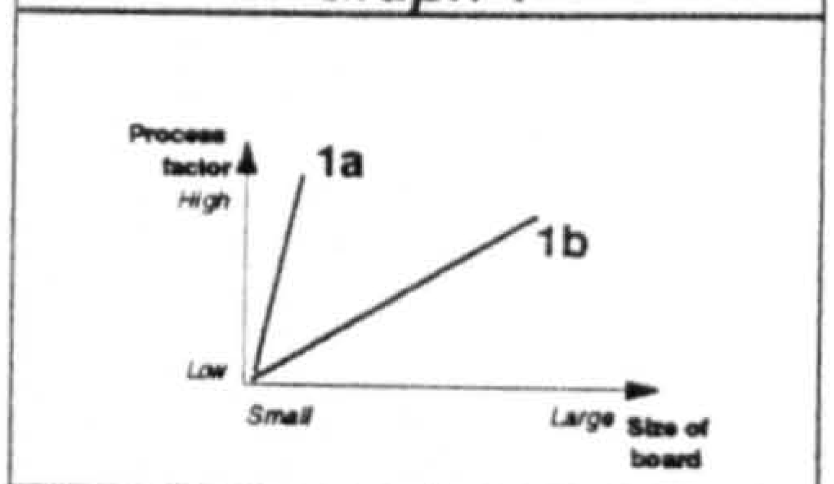
Energy consumption vs. Size of board		
Ranking for ecological impact 1 2 3 4 (5) 6 7 8 9 10 Level of confidence 1 2 3 4 (5)	Approximate relationship with Size of Board. *Select graph from **Column A** and circle number below:* 1a (1b) 2a 2b 3a 3b 4 5a 5b 6a 6b 7	**OR** Sketch ***own*** graphical relationship:  **You may wish to annotate your graph with a comment at the foot of the page.*

Other observations:

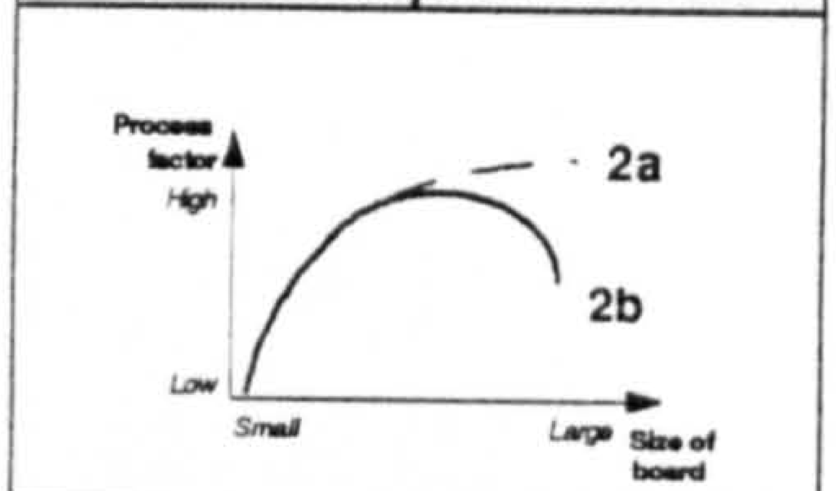
Annotations for graphs:

Column A

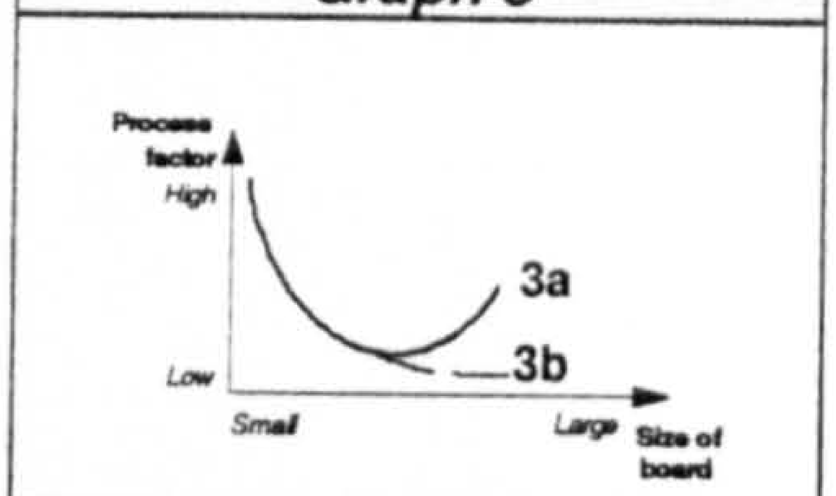
Graph 1



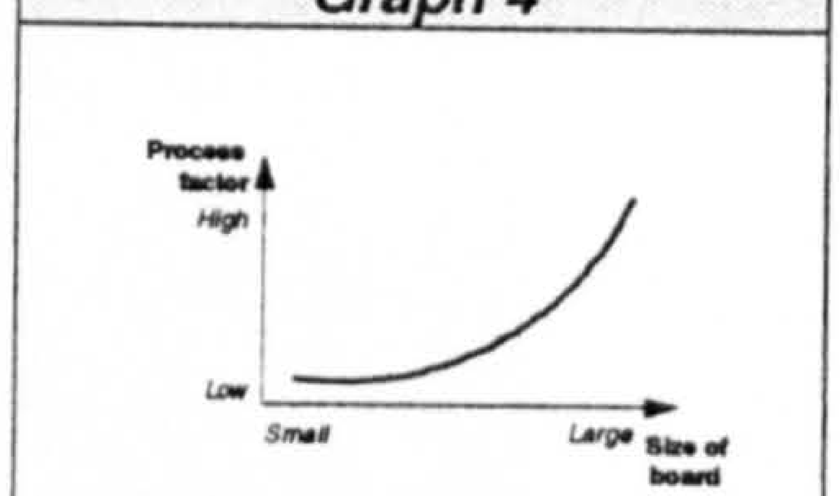
Graph 2



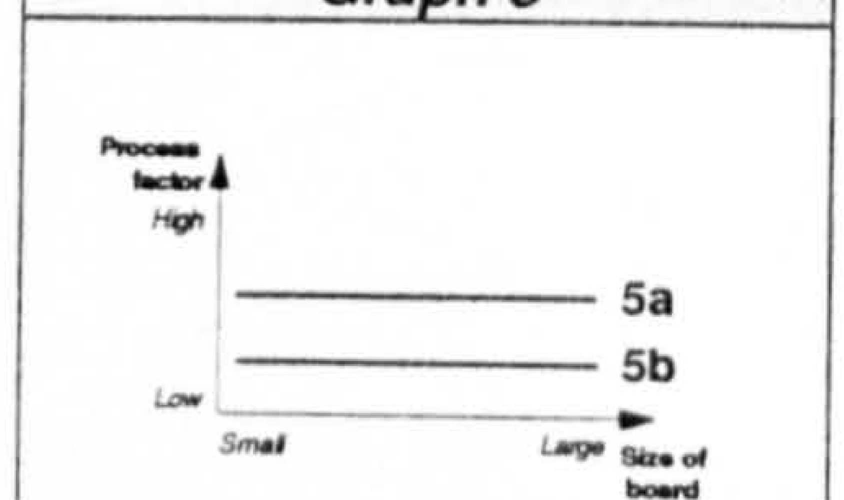
Graph 3



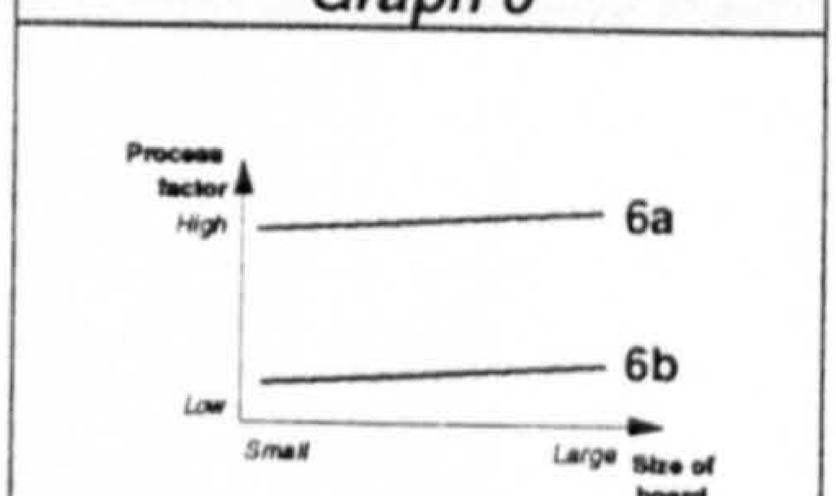
Graph 4



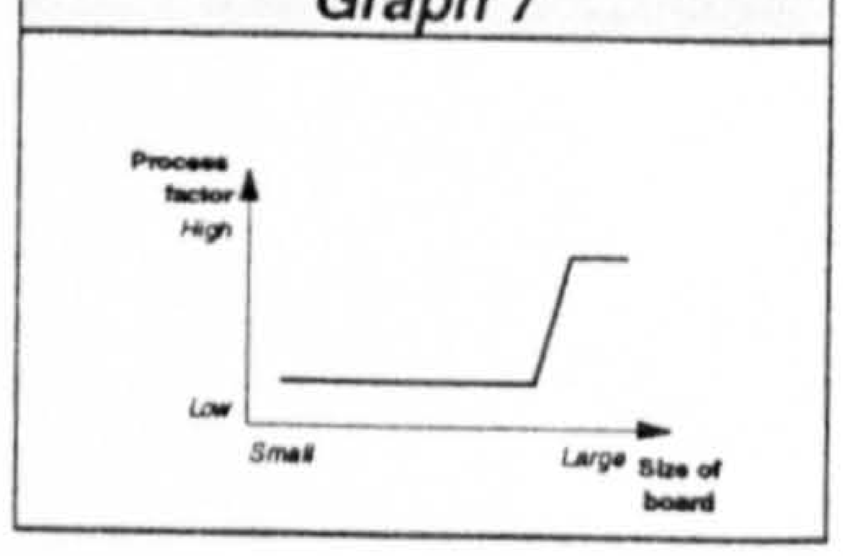
Graph 5



Graph 6



Graph 7



SECTION D End-Of-Life Phase

Ease of disassembly vs. Size of board

Ranking for ecological impact

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

Level of confidence

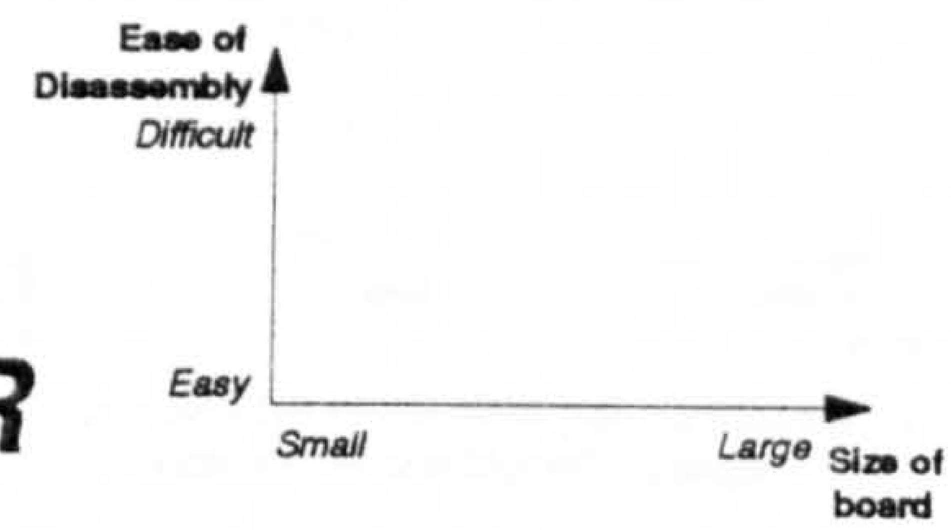
1 2 3 4 (5)

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
(5a) 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship:



**You may wish to annotate your graph with a comment at the foot of the page.*

Ease of components recovery vs. Size of board

Ranking for ecological impact

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

Level of confidence

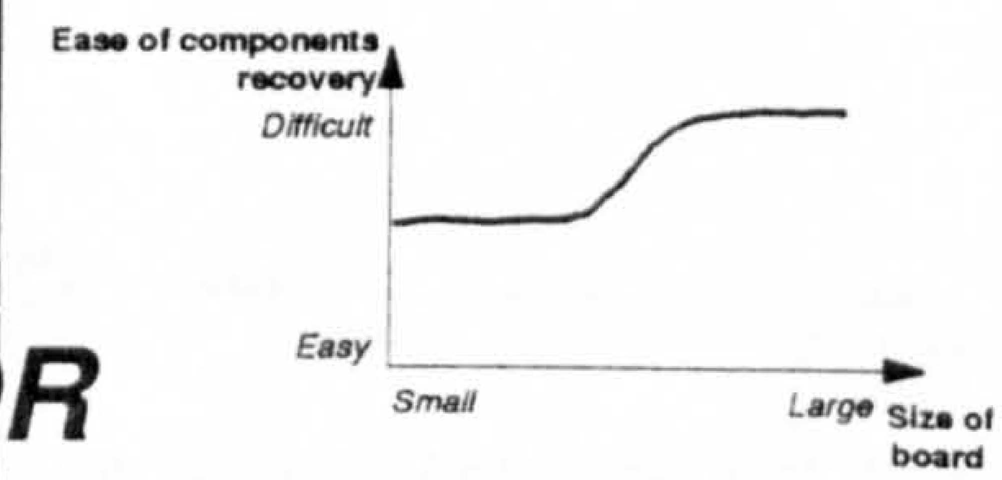
1 2 3 4 (5)

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a 1b
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

Sketch ***own*** graphical relationship:



**You may wish to annotate your graph with a comment at the foot of the page.*

Level of hazardous/ toxic substances vs. Size of board

Ranking for ecological impact

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

Level of confidence

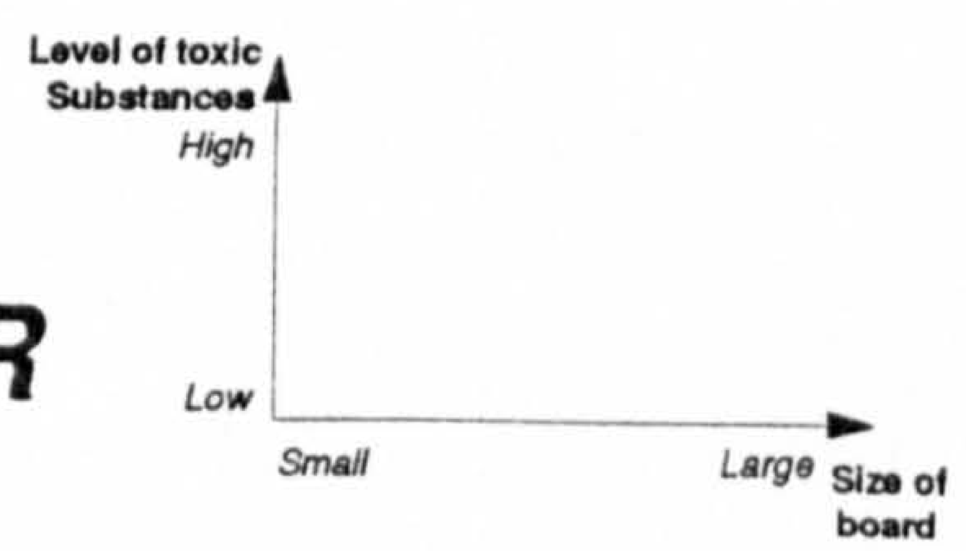
1 2 3 4 (5)

Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*

1a (1b)
2a 2b
3a 3b
4
5a 5b
6a 6b
7

OR

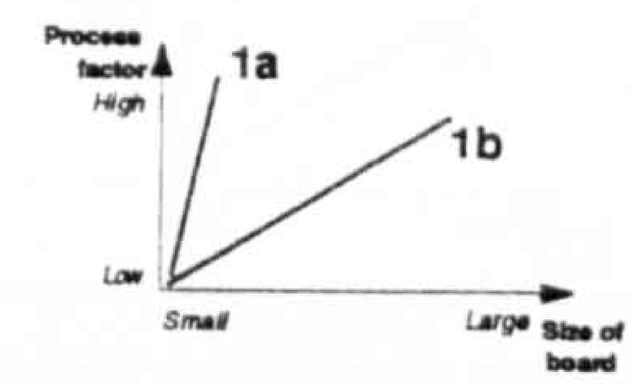
Sketch ***own*** graphical relationship:



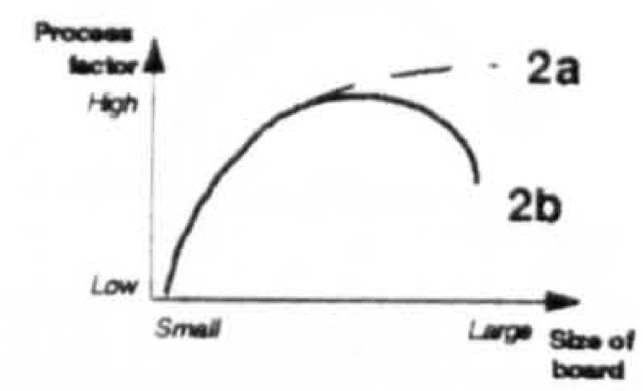
**You may wish to annotate your graph with a comment at the foot of the page.*

Column A

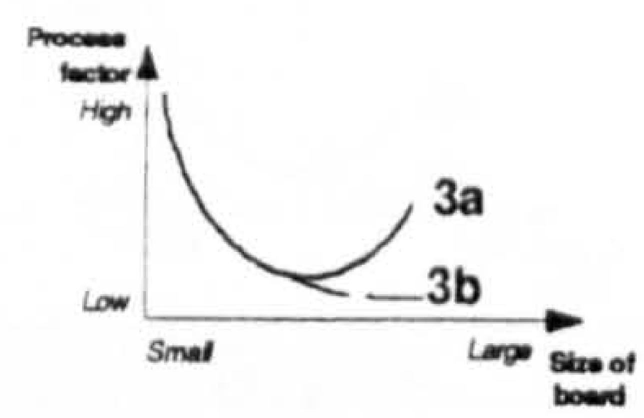
Graph 1



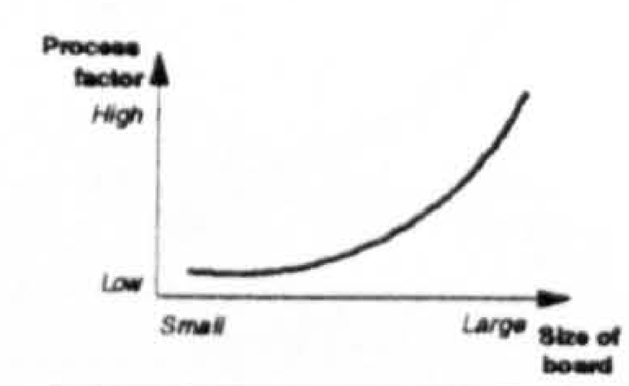
Graph 2



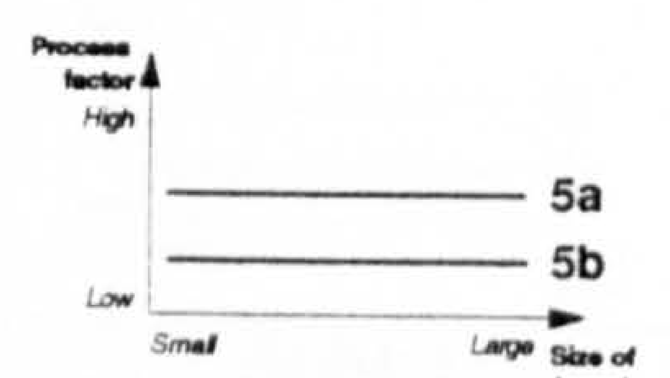
Graph 3



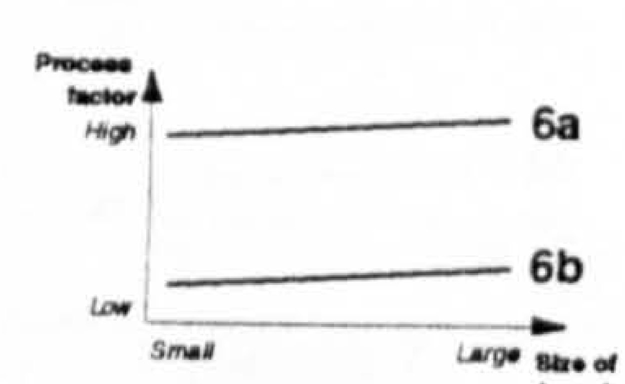
Graph 4



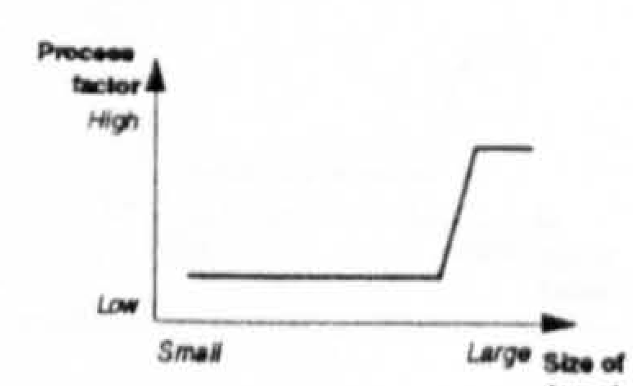
Graph 5



Graph 6



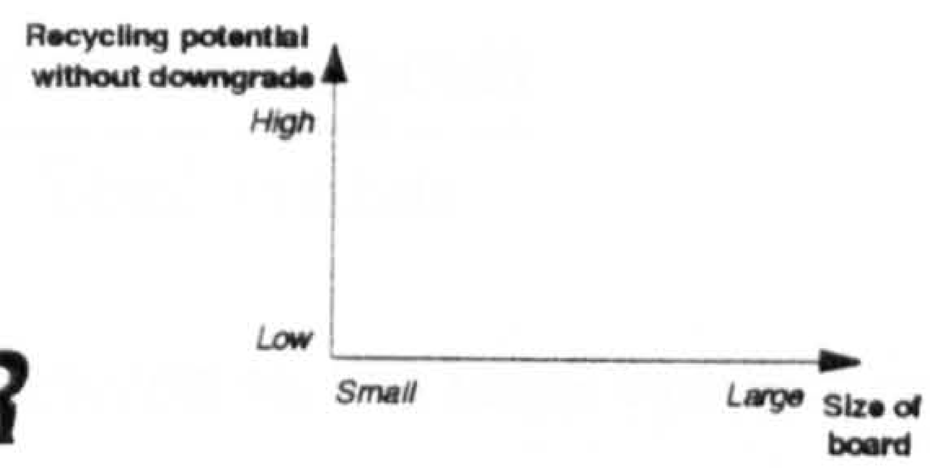
Graph 7



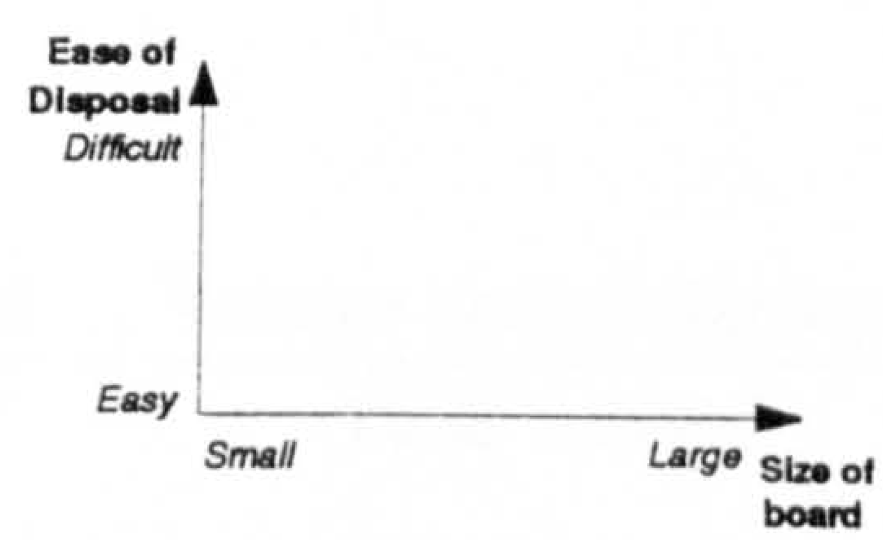
Remarks/ Annotations for graphs:

End-Of-Life Phase (continued)

Recycling potential without downgrade vs. Size of board

Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 (10)	1a 1b 2a 2b 3a 3b 4 5a (5b) 6a 6b 7	**OR**	 *You may wish to annotate your graph with a comment at the foot of the page.*
Level of confidence 1 2 3 4 (5)			

Ease of disposal vs. Size of board

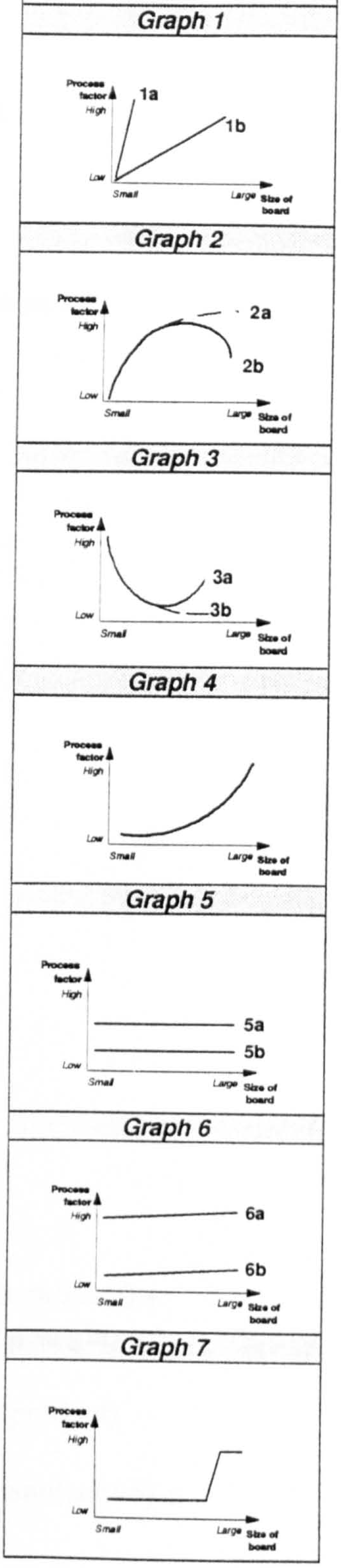
Ranking for ecological impact	Approximate relationship with Size of Board. *Select graph from* ***Column A*** *and circle number below:*		Sketch ***own*** graphical relationship:
1 2 3 4 5 6 7 8 9 (10)	1a 1b 2a 2b 3a 3b 4 5a 5b (6a) 6b 7	**OR**	 *You may wish to annotate your graph with a comment at the foot of the page.*
Level of confidence 1 2 3 4 (5)			

Are there any significant changes in the future likely to occur in the treatment of End-of-Life equipment that will have significant impact on the ecological aspects of such products?

Design for disassembly as a culture. Plastics and other material labelling.

Remarks/ Annotations for graphs:

Column A



APPENDIX B

Derivation of mixed strategy equation

Let α be the ratio of volume recycled to the total volume reprocessed,

$$\alpha = \frac{\text{Volume recycled}}{\text{Total volume}}$$

Let β be the ratio of volume remanufactured to the total volume reprocessed,

$$\beta = \frac{\text{Volume remanufactured}}{\text{Total volume}}$$

Let γ be the ratio of volume resold to the total volume reprocessed,

$$\gamma = \frac{\text{Resale volume}}{\text{Total volume}}$$

Therefore,

$$\alpha + \beta + \gamma = \frac{\text{Volume recycled}}{\text{Total volume}} + \frac{\text{Volume remanufactured}}{\text{Total volume}} + \frac{\text{Resale volume}}{\text{Total volume}}$$

$$= \frac{\text{Total volume}}{\text{Total volume}} = 1$$

Set $\gamma = 1 - (\alpha + \beta)$

Therefore,

Revenue in mixed strategy = α (Revenue for recycling a single product) + β (Revenue for remanufacturing a single product) + γ (Revenue for reselling a single product)

= α (Rev Recycling) + β(Rev Remanufacture) + $[1-(\alpha+\beta)]$ (Rev Resale)

APPENDIX C

Detailed calculations for end-of-life economic models

Recall that the purpose of the economic models in the body of the thesis is to capture all the individual overheads involved within the product system as simple coefficients of manufacturing cost in order to simply the comparison of different end-of-life routes. This appendix contains detailed calculations for the end-of-life economic models derived in chapter 4. It comprises the following sections:

Relate 100	
End-of-life strategy	**Calculation results**
Recycling	Actual estimate/ Model 1
	Model 2
	Model 3
Resale	Actual estimate
	Model 1
	Model 2
	Model 3
Remanufacturing	Actual estimate/ Model 1
	Model 2
	Model 3

Converse 300	
End-of-life strategy	**Calculation results**
Resale	Actual estimate
	Model 1
	Model 2
	Model 3
Remanufacturing	Actual estimate
	Model 1
	Model 2
	Model 3
Recycling	Actual estimate
	Model 1
	Model 2
	Model 3

Euroset 810	
End-of-life strategy	**Calculation results**
Resale	Actual estimate
	Model 1
	Model 2
	Model 3
Remanufacturing	Actual estimate
	Model 1
	Model 2
	Model 3
Recycling	Actual estimate
	Model 1
	Model 2
	Model 3

End-of-life strategy	Product Example
Scrap	Relate 100
Upgrade	Euroset 812

The process to generate individual actual estimates of overhead is shown below for the example of recycling of the Relate 100 together with the sources of data.

Recycling (Relate 100) Model 1/ Actual Estimate

Manufacturing cost, M	£11.55 (†)
Takeback cost (logistics)	£3 (†)
Disassembly and sorting cost	£0.087 (*)
Labour rate	£5 per hour (✻)
Cleaning, etc. assume	2 minute per unit (‡)
Therefore cost of cleaning	£0.167 (‡)
Cost of packaging	£0.010 (‡)
Sub-total (exclude takeback)	£0.264
Value of μ	0.28
Cost of takeback + disassembly + cleaning + packaging is	0.28M
Total disposal weight	129g @ £30 per ton
Cost of disposal/ landfill	£0.0039 (‡)
Total overheads (include takeback)	£3.268 [1]
Overheads exclude takeback	£0.268

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	423g @ £200 per ton
Revenue from sale of ABS	£0.0846 (*)
Copper to be recovered from PCB	
Weight of PCB	63g @£12 per ton
Revenue from sale of PCB	£0.000756 (*)
The following items are reused:	
Microphone (handset):	
Revenue	£0.004 (*)
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04 (✡)
Speaker (handset):	
Revenue	£0.004 (*)
Mixed plastic number keys:	
Revenue	£0.004 (*)
Revenue from recycling and reusing of components	£0.1374 [2]

Revenue per unit is given by:	
(Revenue from recycling/ reusing- overheads)	[2] - [1] = -£3.130
Total number of units returned for processing is 75% of total number manufactured =	375 000 phones (†)

Total revenue	-£1 173 818 [i]

Total number of units manufactured	500000 phones (†)
Selling price of new product, Pn	£29.99 (§)
Cost price to manufacture, Xn	£11.55 (†)
Revenue made from new product= (Pn-Xn)*Total number manufactured =	
	£9 220 000 [ii]

Total revenue made	[i] +[ii] = £8 046 182

Legend for souce of data:

(†) [Maclaren 96] from BT
(‡) Estimated by author
(*) MMU data from [BT 95]
(✠) MMU via Mayer Cohen
(✡) Mayer Cohen
(§) Retail price 1996

Recycling (Relate 100) Model 2

Manufacturing cost, M	£11.55
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Therefore overheads cost is (0.76*0.125)*£11.55	£1.09
Cost of takeback + disassembly + packaging + cleaning	£4.09
Total disposal weight	129g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads	£4.098 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	423g @ £200 per ton
Revenue from sale of ABS	£0.0846
Copper to be recovered from PCB	
Weight of PCB	63g @£12 per ton
Revenue from sale of PCB	£0.000756
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.004
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1374 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] = - £3.961
Total number of units to be processed were	375 000
Total revenue made	- £1 485 329

Recycling (Relate 100) Model 3

Manufacturing cost, M	£11.55
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Correction factor	0.12
Therefore overheads cost is (0.76*0.125*0.12)*£11.55	£0.13
Cost of takeback + disassembly + packaging + cleaning	£3.13
Total disposal weight	129g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads	£3.135 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	423g @ £200 per ton
Revenue from sale of ABS	£0.0846
Copper to be recovered from PCB	
Weight of PCB	63g @£12 per ton
Revenue from sale of PCB	£0.000756
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.004
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1374 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] =
	- £2.998
Total number of units to be processed were	375 000
Total revenue made	- £1 124 189

Resale (Relate 100) Actual Estimate

Manufacturing cost	£11.55
Take back cost	£3
Transport to second market	£1.5
Inspection/ Cleaning (2 min @ 5 pounds per hour)	£0.167
Testing	£0.02
Packaging	£0.08
Total overheads for each phone	£4.767
Overheads exclude take back and transport cost	£0.267

Total number of units manufactured	500000 phones
Selling price of new product, Pn	£29.99
Cost price to manufacture, Xn	£11.55
Revenue made from new product= (Pn-Xn)*Total number manufactured =	£9 220 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	375 000 phones
Selling price of resale phone, Pr	£14.55
EOL processing price, Xr	£4.767
Revenue per phone is Pr - Xr	£9.783
Total second market revenue = (Pr-Xr)*Total units processed =	£3 668 625 [2]

Total revenue made	[1] +[2] = £12 888 625

Resale (Relate 100) Model 1

Manufacturing cost, M	£11.55
Take back costs (logistics + shipping to second market)	40 %M
	£4.62
Labour (Inspection/testing/packaging)	5 %M
	£0.5775
Labels etc.	2 %M
	£0.231
Total overheads for each phone	£5.429
Value of α	0.47
Cost of takeback + labour + labels, etc.	0.47M

Total number of units manufactured	500 000	phones
Selling price of new product, Pn	£29.99	
Cost price to manufacture, Xn	£11.55	
Revenue made from new product = (Pn-Xn)*Total number manufactured =		
	£9 220 000 [1]	

Total number of units returned for processing is 75% of total number manufactured =		
	375 000	phones
Selling price of resale phone, Pr	£14.55	
EOL processing price, Xr	αM =	
	£5.429	
Revenue made per unit	£9.122	
Total second market revenue = (Pr-Xr)*Total units processed=		
	£3 420 563 [2]	

Total revenue made	[1] +[2] =
	£12 640 563

Resale (Relate 100) Model 2

Manufacturing cost, M	£11.55	
Take back costs (logistics + shipping to second market)	£4.5	
Summation of Cleaning/ Packaging/ Testing ratios:		
0.38 + 0.181 + 0.045=	0.606	
Therefore overheads cost is 0.606*0.125*£11.55	£0.87	
Total overheads for each phone	£5.37	
Total number of units manufactured	500 000	phones
Selling price of new product, Pn	£29.99	
Cost price to manufacture, Xn	£11.55	
Revenue made from new product= (Pn-Xn)*Total number manufactured =		
	£9 220 000 [1]	

Total number of units returned for processing is 75% of total number manufactured =		
	375 000	phones
Selling price of resale phone, Pr	£14.55	
EOL processing price, Xr	£5.37	
Revenue made per unit	£9.18	
Total second market revenue= (Pr-Xr)*Total units processed =		
	£3 440 658 [2]	

Total revenue made	[1] +[2] =
	£12 660 658

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Resale (Relate 100) Model 3

Manufacturing cost, M	£11.55	
Take back costs (logistics + shipping to second market)	£4.5	
Summation of Cleaning/ Packaging/ Testing ratios:		
0.38 + 0.181 + 0.045=	0.606	
Therefore overheads cost is 0.606*0.125*£11.55*0.12	£0.10	
Total overheads for each phone	£4.60	
Total number of units manufactured	500 000	phones
Selling price of new product, Pn	£29.99	
Cost price to manufacture, Xn	£11.55	
Revenue made from new product= (Pn-Xn)*Total number manufactured =		
	£9 220 000 [1]	

Total number of units returned for processing is 75% of total number manufactured =		
	375 000	phones
Selling price of resale phone, Pr	£14.55	
EOL processing price, Xr	£4.60	
Revenue made per unit	£9.95	
Total second market revenue= (Pr-Xr)*Total units processed =		
	£ 3 729 379 [2]	

Total revenue made	[1] +[2] =
	£ 12 949 379

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Relate 100)
Model 1/ Actual Estimate

Manufacturing cost, M	£11.55		
Takeback cost (logistics)	£3		
Disassembly and sorting cost	£0.087		
Labour rate	£5 per hour		
Cleaning, etc. assuming	2 minutes per unit		
Therefore cost of cleaning is	£0.167		
Part(s) replacement	£0.000	(min.)	
Part(s) replacement using (3/8)M model	£4.331	(max.)	
Part(s) replacement	£2.166	(ave.)	
Reassembly	£0.087	(manual)	
Testing	£0.020		
Cost of packaging	£0.080		
Cost (exclude takeback)	£0.441	(min.)	
	£2.606	(ave.)	
	£4.772	(max.)	
Total overheads	£3.441	(min.)	[1]
	£5.606	(ave.)	[1]
	£7.772	(max.)	[1]
Value of β	0.30	(min).	
	0.49	(ave.)	
	0.67	(max.)	

Total number of units returned for processing were	375 000	
Selling price of refurbished phone	£14.55	[2]
Revenue per phone	[2]-[1] =	
	£11.109	(max.)
	£8.944	(ave.)
	£6.778	(min.)
Total revenue for 375 000 phones	£4 166 000	(max.)
	£3 353 891	(ave.)
	£2 541 781	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Remanufacturing (Relate 100) Model 2

Manufacturing cost, M	£11.55		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general repocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*£11.55	£3.609		
Overheads (exclude takeback) for:			
Part(s) replacement	£1.444	(min.)	
Part(s) replacement using (3/8)M model	£5.775	(max.)	
Part(s) replacement	£3.609	(ave.)	
Total overheads (include takeback)	£4.444	(min.)	[1]
	£6.609	(ave.)	[1]
	£8.775	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone	£14.55	[2]
Revenue per phone is given by	[2]-[1] =	
	£10.106	(max.)
	£7.941	(ave.)
	£5.775	(min.)
Total revenue for 375 000 phones	£3 789 844	(max.)
	£2 977 734	(ave.)
	£2 165 625	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Relate 100) Model 3

Manufacturing cost, M	£11.55		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general reprocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Correction factor	0.67		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*0.67*£11.55	£2.418		
Overheads (exclude takeback) for:			
Part(s) replacement	£0.967	(min.)	
Part(s) replacement using (3/8)M model	£3.869	(max.)	
Part(s) replacement	£2.418	(ave.)	
Total overheads (include takeback)	£3.967	(min.)	[1]
	£5.418	(ave.)	[1]
	£6.869	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone	£14.55	[2]
Revenue per phone is given by	[2]-[1] =	
	£10.583	(max.)
	£9.132	(ave.)
	£7.681	(min.)
Total revenue for 375000 phones	£ 3 968 508	(max.)
	£ 3 424 395	(ave.)
	£ 2 880 281	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Resale (Converse 300) Actual Estimate

Manufacturing cost	£30
Take back cost	£3
Transport to second market	£1.5
Inspection/ Cleaning (2 min @ 5 pounds per hour)	£0.167
Testing	£0.02
Packaging	£0.08
Total overheads for each phone	£4.767
Overheads exclude take back and transport cost	£0.267

Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£74.99
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	£22 495 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	375 000 phones
Selling price of resale phone, Pr	£36
EOL processing price, Xr	£4.767
Revenue per phone is Pr - Xr	£31.233
Total second market revenue= (Pr-Xr)*Total units processed =	£11 712 375 [2]

Total revenue made	[1] +[2] = £34 207 375

Resale (Converse 300) Model 1

Manufacturing cost, M	£30
Take back costs (logistics + shipping to second market) (estimated from Relate 100)	40%M £12
Labour cost (Inspection/testing/packaging)	5 %M £1.5
Labels etc.	2 %M £0.60
Total overheads for each phone	£14.1
Value of α	0.47
Cost of takeback + labour +labels, etc.	0.47M

Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£74.99
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	£22 495 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	375 000 phones
Selling price of resale phone, Pr	£36
EOL processing cost, Xr	αM = £14.1
Revenue made per unit	£21.9
Total second market revenue is given by (Pr-Xr)*Total units processed	£8 212 500 [2]

Total revenue made	[1] +[2] = £30 707 500

Resale (Converse 300) Model 2

Manufacturing cost, M	£30	
Take back costs (logistics + shipping to second market)	£4.5	
Summation of Cleaning/ Packaging/ Testing ratios:		
0.38 + 0.181 + 0.045=	0.606	
Ratio for general reprocessing	0.125	
Therefore overheads cost is 0.606*0.125*£30	£2.27	
Total overheads for each phone	£6.77	
Total number of units manufactured	500000	phones
Selling price of new product, Pn	£74.99	
Cost price to manufacture, Xn	£30	
Revenue made from new product= (Pn-Xn)*Total number manufactured =		
	£22 495 000 [1]	

Total number of units returned for processing is 75% of total number manufactured =		
	375 000	phones
Selling price of resale phone, Pr	£36	
EOL processing price, Xr	£6.77	
Revenue made per unit	£29.23	
Total second market revenue= (Pr-Xr)*Total units processed =		
	£10 960 313 [2]	

Total revenue made	[1] +[2] =
	£33 455 313

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Resale (Converse 300) Model 3

Manufacturing cost, M	£30
Take back costs (logistics + shipping to second market)	£4.5
Summation of Cleaning/ Packaging/ Testing ratios:	
0.38 + 0.181 + 0.045=	0.606
Ratio for general reprocessing	0.125
Correction factor	0.12
Therefore overheads cost is 0.606*0.125*30*0.12	£0.27
Total overheads for each phone	£4.77
Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£74.99
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	
	£22 495 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	
	375 000 phones
Selling price of resale phone, Pr	£36
EOL processing price, Xr	£4.77
Revenue made per unit	£31.23
Total second market revenue= (Pr-Xr)*Total units processed =	
	£11 710 238 [2]

Total revenue made	[1] +[2] =
	£ 34 205 238

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Converse 300) Actual Estimate

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Disassembly and sorting cost	£0.1496		
Labour rate	£5 per hour		
Cleaning, etc. assuming	2 minutes per unit		
Therefore cost of cleaning is	£0.167		
Part(s) replacement	£0.000	(min.)	
Part(s) replacement using (3/8)M model	£11.25	(max.)	
Part(s) replacement	£5.625	(ave.)	
Reassembly	£0.15	(manual)	
Testing	£0.020		
Cost of packaging	£0.080		
Cost (exclude takeback)	£0.566	(min.)	
	£6.191	(ave.)	
	£11.816	(max.)	
Total overheads	£3.566	(min.)	[1]
	£9.191	(ave.)	[1]
	£14.816	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone	£36	[2]
Revenue per phone	[2]-[1] =	
	£32.434	(max.)
	£26.809	(ave.)
	£21.184	(min.)
Total revenue for 375 000 phones	£12 162 800	(max.)
	£10 053 425	(ave.)
	£7 944 050	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Remanufacturing (Converse 300) Model 1

Manufacturing cost, M	£30.00		
Value of β (estimated from Relate 100)	0.30	(min.)	
	0.49	(ave.)	
	0.67	(max.)	
Cost of Takeback + Disassembly + Clean + Reassembly + Testing + Packaging:			
0.30M =	£9	(min.)	[1]
0.49M =	£14.7	(ave.)	[1]
0.67M =	£20.1	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£36	[2]
Revenue per phone is given by	[2]-[1] =	
	£27.000	(max.)
	£21.300	(ave.)
	£15.900	(min.)
Total revenue for 375 000 phones	£10 125 000	(max.)
	£7 987 500	(ave.)
	£5 962 500	(min.)

Remanufacturing (Converse 300) Model 2

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general repocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*£30	£9.375		
Overheads (exclude takeback) for:			
Part(s) replacement	£3.750	(min.)	
Part(s) replacement using (3/8)M model	£15.000	(max.)	
Part(s) replacement	£9.375	(ave.)	
Total overheads (include takeback)	£6.750	(min.)	[1]
	£12.375	(ave.)	[1]
	£18.000	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£36	[2]
Revenue per phone is given by	[2]-[1] =	
	£29.250	(max.)
	£23.625	(ave.)
	£18.000	(min.)
Total revenue for 375000 phones	£10 968 750	(max.)
	£8 859 375	(ave.)
	£6 750 000	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Converse 300) Model 3

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general reprocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Correction factor	0.67		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*0.67*£30	£6.281		
Overheads (exclude takeback) for:			
Part(s) replacement	£2.513	(min.)	
Part(s) replacement using (3/8)M model	£10.050	(max.)	
Part(s) replacement	£6.281	(ave.)	
Total overheads (include takeback)	£5.513	(min.)	[1]
	£9.281	(ave.)	[1]
	£13.050	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£36	[2]
Revenue per phone is given by	[2]-[1] =	
	£30.488	(max.)
	£26.719	(ave.)
	£22.950	(min.)
Total revenue for 375 000 phones	£ 11 432 813	(max.)
	£ 10 019 531	(ave.)
	£ 8 606 250	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Recycling (Converse 300) Actual Estimate

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Disassembly and sorting cost	£0.1496
Labour rate	£5 per hour
Cleaning, etc. assume	2 minute per unit
Therefore cost of cleaning	£0.167
Cost of packaging	£0.010
Sub-total (exclude takeback)	£0.326
Total disposal weight	130g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads (include takeback)	£3.326 [1]
Overheads exclude takeback	£0.326

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	383g @ £200 per ton
Revenue from sale of ABS	£0.0766
Copper to be recovered from PCB	
Weight of PCB	135g @ £12 per ton
Revenue from sale of PCB	£0.009
Lead to be recovered	
Weight of lead	88g @ £160 per ton
Revenue from sale of lead	£0.01408
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.005
Revenue from recycling and reusing of components	£0.15468 [2]

Revenue per unit is given by:	
(Revenue from recycling/ reusing- overheads)	[2] - [1] =
	-£3.172
Total number of units to be processed were	375 000
Total revenue	-£1 189 345

Recycling (Converse 300) Model 1

Manufacturing cost, M	£30
Value of μ (estimated from Relate 100)	0.28
Therefore cost of takeback + disassembly + packaging	0.28M
Total disposal weight	130g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads (include takeback)	£8.404 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	383g @ £200 per ton
Revenue from sale of ABS	£0.0766
Copper to be recovered from PCB	
Weight of PCB	135g @ £12 per ton
Revenue from sale of PCB	£0.009
Lead to be recovered	
Weight of lead	88g @ £160 per ton
Revenue from sale of lead	£0.01408
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.005
Revenue from recycling and reusing of components	£0.15468 [2]

Revenue per unit is given by:	
(Revenue from recycling/ reusing- overheads)	[2] - [1] =
	-£8.249
Total number of units to be processed were	375 000
Total revenue	-£3 093 458

Recycling (Converse 300) Model 2

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Therefore overheads cost is (0.76*0.125)*£30	£2.84
Cost of takeback + disassembly + packaging + cleaning	£5.84
Total disposal weight	130g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads	£5.846 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	383g @ £200 per ton
Revenue from sale of ABS	£0.0766
Copper to be recovered from PCB	
Weight of PCB	135g @ £12 per ton
Revenue from sale of PCB	£0.009
Lead to be recovered	
Weight of lead	88g @ £160 per ton
Revenue from sale of lead	£0.01408
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.005
Revenue from recycling and reusing of components	£0.15468 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] =
	- £5.692
Total number of units to be processed were	375 000
Total revenue made	- £2 134 384

Recycling (Converse 300) Model 3

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Correction factor	0.12
Therefore overheads cost is (0.76*0.125)*0.12*£30	£0.34
Cost of takeback + disassembly + packaging + cleaning	£3.34
Total disposal weight	130g @ £30 per ton
Cost of disposal/ landfill	£0.0039
Total overheads	£3.345 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	383g @ £200 per ton
Revenue from sale of ABS	£0.0766
Copper to be recovered from PCB	
Weight of PCB	135g @ £12 per ton
Revenue from sale of PCB	£0.009
Lead to be recovered	
Weight of lead	88g @ £160 per ton
Revenue from sale of lead	£0.01408
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.005
Revenue from recycling and reusing of components	£0.15468 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] =
	- £3.190
Total number of units to be processed were	375 000
Total revenue made	- £ 1 196 370

Resale (Euroset 812) Actual Estimate

Manufacturing cost	£30
Take back cost	£3
Transport to second market	£1.5
Inspection/ Cleaning (2 min @ 5 pounds per hour)	£0.083
Testing	£0.02
Packaging	£0.08
Total overheads for each phone	£4.683
Overheads exclude take back and transport cost	£0.183

Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£80
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	£25 000 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	375 000 phones
Selling price of resale phone, Pr	£39
EOL processing price, Xr	£4.683
Revenue per phone is Pr - Xr	£34.317
Total second market revenue= (Pr-Xr)*Total units processed =	£12 868 875 [2]

Total revenue made	[1] +[2] = £37 868 875

Resale (Euroset 812) Model 1

Manufacturing cost, M	£30
Take back costs (logistics + shipping to second market)	
(estimated from Relate 100)	40%M
	£12
Labour cost (Inspection/testing/packaging)	5 %M
	£1.5
Labels etc.	2 %M
	£0.60
Total overheads for each phone	£14.1
Value of α	0.47
Cost of takeback + labour +labels, etc.	0.47M

Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£80
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	
	£25 000 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	
	375 000 phones
Selling price of resale phone, Pr	£39
EOL processing cost, Xr	αM =
	£14.1
Revenue made per unit	£24.9
Total second market revenue is given by (Pr-Xr)*Total units processed	
	£9 337 500 [2]

Total revenue made	[1] +[2] =
	£34 337 500

Resale (Euroset 812) Model 2

Manufacturing cost, M	£30
Take back costs (logistics + shipping to second market)	£4.5
Summation of Cleaning/ Packaging/ Testing ratios:	
0.38 + 0.181 + 0.045=	0.606
Ratio for general reprocessing	0.125
Therefore overheads cost is 0.606*0.125*£30	£2.27
Total overheads for each phone	£6.77
Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£80
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	
	£25 000 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	
	375 000 phones
Selling price of resale phone, Pr	£39
EOL processing price, Xr	£6.77
Revenue made per unit	£32.23
Total second market revenue= (Pr-Xr)*Total units processed =	
	£12 085 313 [2]

Total revenue made	[1] +[2] =
	£37 085 313

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Resale (Euroset 812) Model 3

Manufacturing cost, M	£30
Take back costs (logistics + shipping to second market)	£4.5
Summation of Cleaning/ Packaging/ Testing ratios:	
0.38 + 0.181 + 0.045=	0.606
Ratio for general reprocessing	0.125
Correction factor	0.12
Therefore overheads cost is 0.606*0.125*£30*0.12	£0.27
Total overheads for each phone	£4.77
Total number of units manufactured	500 000 phones
Selling price of new product, Pn	£80
Cost price to manufacture, Xn	£30
Revenue made from new product= (Pn-Xn)*Total number manufactured =	£25 000 000 [1]

Total number of units returned for processing is 75% of total number manufactured =	375 000 phones
Selling price of resale phone, Pr	£39
EOL processing price, Xr	£4.77
Revenue made per unit	£34.23
Total second market revenue= (Pr-Xr)*Total units processed =	£12 835 238 [2]

Total revenue made	[1] +[2] = £ 37 835 238

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Euroset 812) Actual Estimate

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Disassembly and sorting cost	£0.0604		
Labour rate	£5 per hour		
Cleaning, etc. assuming	2 minutes per unit		
Therefore cost of cleaning is	£0.167		
Part(s) replacement	£0.000	(min.)	
Part(s) replacement using (3/8)M model	£11.25	(max.)	
Part(s) replacement	£5.625	(ave.)	
Reassembly	£0.060	(manual)	
Testing	£0.020		
Cost of packaging	£0.080		
Cost (exclude takeback)	£0.387	(min.)	
	£6.012	(ave.)	
	£11.637	(max.)	
Total overheads	£3.387	(min.)	[1]
	£9.012	(ave.)	[1]
	£14.637	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone	£39	[2]
Revenue per phone	[2]-[1] =	
	£35.613	(max.)
	£29.988	(ave.)
	£24.363	(min.)
Total revenue for 375000 phones	£13 354 700	(max.)
	£11 245 325	(ave.) [i]
	£9 135 950	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Assuming a total of 500 000 new phones are manufactured with £30 and £80 as cost and selling price respectively, product revenue is therefore =

	£(80-30)*500 000
	£25 000 000 [ii]
The total revenue made	[i] + [ii] =
	£36 245 325

Remanufacturing (Euroset 812) Model 1

Manufacturing cost, M	£30.00		
Value of β (estimated from Relate 100)	0.30	(min.)	
	0.49	(ave.)	
	0.67	(max.)	
Cost of Takeback + Disassembly + Clean + Reassembly + Testing + Packaging:			
0.30M =	£9	(min.)	[1]
0.49M =	£14.7	(ave.)	[1]
0.67M =	£20.1	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£39	[2]
Revenue per phone is given by	[2]-[1] =	
	£30.000	(max.)
	£24.300	(ave.)
	£18.900	(min.)
Total revenue for 375 000 phones	£11 250 000	(max.)
	£9 112 500	(ave.)
	£7 087 500	(min.)

Remanufacturing (Euroset 812) Model 2

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general repocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*£30	£9.375		
Overheads (exclude takeback) for:			
Part(s) replacement	£3.750	(min.)	
Part(s) replacement using (3/8)M model	£15.000	(max.)	
Part(s) replacement	£9.375	(ave.)	
Total overheads (include takeback)	£6.750	(min.)	[1]
	£12.375	(ave.)	[1]
	£18.000	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£39	[2]
Revenue per phone is given by	[2]-[1] =	
	£32.250	(max.)
	£26.625	(ave.)
	£21.000	(min.)
Total revenue for 375 000 phones	£12 093 750	(max.)
	£9 984 375	(ave.)
	£7 875 000	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Remanufacturing (Euroset 812) Model 3

Manufacturing cost, M	£30		
Takeback cost (logistics)	£3		
Summation of disassembly / Cleaning/ Reassembly/Testing/Packaging ratios:			
0.197 + 0.38 + 0.197 + 0.045 + 0.181 =	1		
Cost ratio for general reprocessing	0.125		
Ratio for parts replacement (assume average cost)	0.1875		
Correction factor	0.67		
Therefore cost of reprocessing is given by			
1*(0.125 + 0.1875)*0.67*£30	£6.281		
Overheads (exclude takeback) for:			
Part(s) replacement	£2.513	(min.)	
Part(s) replacement using (3/8)M model	£10.050	(max.)	
Part(s) replacement	£6.281	(ave.)	
Total overheads (include takeback)	£5.513	(min.)	[1]
	£9.281	(ave.)	[1]
	£13.050	(max.)	[1]

Total number of units returned for processing were	375 000	
Selling price of refurbished phone is	£39	[2]
Revenue per phone is given by	[2]-[1] =	
	£33.488	(max.)
	£29.719	(ave.)
	£25.950	(min.)
Total revenue for 375 000 phones	£ 12 557 813	(max.)
	£ 11 144 531	(ave.)
	£ 9 731 250	(min.)

*Landfill/ disposal costs were excluded as they were variable and insignificant (<£0.01).

Disassembly ratio	0.197
Testing ratio	0.045
Packaging ratio	0.181
Cleaning ratio	0.38
Resassembly ratio	0.197

Recycling (Euroset 812) Actual Estimate

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Disassembly and sorting cost	£0.0604
Labour rate	£5 per hour
Cleaning, etc. assume	2 minute per unit
Therefore cost of cleaning	£0.167
Cost of packaging	£0.010
Sub-total (exclude takeback)	£0.327
Total disposal weight	83g @ £30 per ton
Cost of disposal/ landfill	£0.0025
Total overheads (include takeback)	£3.327 [1]
Overheads exclude takeback	£0.327

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	337g @ £200 per ton
Revenue from sale of ABS	£0.0674
Copper to be recovered from PCB	
Weight of PCB	83g @ £12 per ton
Revenue from sale of PCB	£0.009
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1304 [2]

Revenue per unit is given by:	
(Revenue from recycling/ reusing- overheads)	[2] - [1] =
	-£3.107
Total number of units to be processed were	375 000
Total revenue	-£1 165 000 [i]

To be continued on next page.

Assuming a total of 500 000 new phones are manufactured with £30 and £80 as cost and selling price respectively, product revenue is therefore =	
	£(80-30)*500 000
	£25 000 000 [ii]
The total revenue made	[i] + [ii] =
	£23 835 000

Recycling (Euroset 812) Model 1

Manufacturing cost, M	£30
Value of μ (estimated from Relate 100)	0.28
Therefore cost of takeback + disassembly + packaging is	0.28M
Total disposal weight	83g @ £30 per ton
Cost of disposal/ landfill	£0.0025
Total overheads (include takeback)	£8.402 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	337g @ £200 per ton
Revenue from sale of ABS	£0.0674
Copper to be recovered from PCB	
Weight of PCB	83g @ £12 per ton
Revenue from sale of PCB	£0.009
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1304 [2]

Revenue per unit is given by:	
(Revenue from recycling/ reusing- overheads)	[2] - [1] =
	-£8.272
Total number of units to be processed were	375 000
Total revenue	-£3 102 034

Recycling (Euroset 812) Model 2

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Therefore overheads cost is (0.76*0.125)*£30	£2.84
Cost of takeback + disassembly + packaging + cleaning	£5.84
Total disposal weight	83g @ £30 per ton
Cost of disposal/ landfill	£0.0025
Total overheads	£5.845 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	337g @ £200 per ton
Revenue from sale of ABS	£0.0674
Copper to be recovered from PCB	
Weight of PCB	83g @ £12 per ton
Revenue from sale of PCB	£0.009
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1304 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] =
	- £5.715
Total number of units to be processed were	375 000
Total revenue made	- £2 142 971

Recycling (Euroset 812) Model 3

Manufacturing cost, M	£30
Takeback cost (logistics)	£3
Summation of disassembly/ Cleaning/Packaging ratios:	
0.197 + 0.380 + 0.181=	0.758
Correction factor	0.12
Therefore overheads cost is (0.76*0.125)*0.12*£30	£0.34
Cost of takeback + disassembly + packaging + cleaning	£3.34
Total disposal weight	83g @ £30 per ton
Cost of disposal/ landfill	£0.0025
Total overheads	£3.344 [1]

The following materials are to be recycled:	
ABS to be recycled	
Weight of ABS	337g @ £200 per ton
Revenue from sale of ABS	£0.0674
Copper to be recovered from PCB	
Weight of PCB	83g @ £12 per ton
Revenue from sale of PCB	£0.009
The following items are reused:	
Microphone (handset):	
Revenue	£0.004
Gold phone cord connectors:	
Total number	4 @ 1p each
Revenue	£0.04
Speaker (handset):	
Revenue	£0.006
Mixed plastic number keys:	
Revenue	£0.004
Revenue from recycling and reusing of components	£0.1304 [2]

Revenue per unit is given by:	
(Rev from recycling/reusing - overheads)	[2] - [1] =
	- £3.213
Total number of units to be processed were	375 000
Total revenue made	- £1 204 946

Scrap Example (Relate 100)

Weight of Relate 100	695g	
In tons	0.000684 tons	
Cost per ton to landfill	£30	
Cost per phone to landfill	£0.02052	
Total units to landfill/ dispose	375 000	
Landfill/ Disposal cost	£7695	[1]
Takeback cost per phone unit	£3	
Total takeback costs for 357 000 units	£1 125 000	[2]
Grand total	[1] + [2] = £1 132 695	

Upgrade Example (Euroset 812)

Base unit

Manufacturing cost of Siemens 812	£30	
Total number manufactured	500 000 phones	
Selling price of each	£80	
Revenue from new product is therefore	(80-30)*500 000= £25 000 000 pounds or £25 million	[1]

Video attachment module

Manufacturing cost	£45	
Selling price	£100 pounds	
Let numberof units sold be	75% of 500 000= 375 000 units	
Revenue from video module is therefore	(100-45)*375 000 = £20.63 million	[2]
Total revenue is given by	[1] + [2] = £(25+20.63) million = £45.63 million	