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An Integrated Approach to Planning of Recycling Activities for the Waste from Electrical and Electronic Equipment

By

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A Doctoral Thesis

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SYNOPSIS

This thesis reports on the research undertaken to improve the end-of-life management of Waste from Electrical and Electronic Equipment (WEEE) through the generation of bespoke recycling process plans for various electrical and electronic products. The principle objective of this research is to develop an integrated framework to incorporate the related product, process and legislative information during the end-of-life management to promote sustainable practices of processing of such waste.

The research contributions are divided into three major parts. The first part reviews the relevant literature in the areas of environmental concerns related to the electrical and electronic recovery sector and end-of-life product recovery decision support tools. The second part investigates the 'Recycling Process Planning' framework which incorporates product evaluation, legislative compliance monitoring, and an ecological and economical assessment to generate bespoke eco-efficient recycling process plans for recovery and recycling of electrical and electronic equipment The third part includes the design and implementation of a novel computer aided recycling process planner that demonstrates the application of recycling process planning framework and the associated ecological and economical assessment methodology to identify the most appropriate end-of-life options for WEEE.

The validity of the research concept has been demonstrated via three case studies. The results from these case studies have highlighted the impact that the proposed recycling process planning framework could have in identifying many improvements which could be made in current recovery and recycling practices through adoption of a systematical approach for generation of recycling process plans based on the most up-to-date information and knowledge on recycling processes.

In summary, this research has generated practical and powerful models and tools to improve the environmental and economical performance of WEEE recycling and to provide invaluable support for long term sustainability of the electrical and electronic recovery sector.

ABBREVIATIONS

AATF	:	Approved Authorised Treatment Facility
AP	:	Actual Performance
BCS	:	Best Case Scenario
BFR	:	Brominated Flame Retardant
CAPP	:	Computer Aided Process Planning
CA*R*PP	:	Computer Aided Recycling Process Planning
C*E*PR	:	Combined Eco^2 Performance Ratio
DCF	:	Designated Collection Facility
DfD	:	Design for Disassembly
DfE	:	Design for Environment
DfR	:	Design for Recycling
DTS	:	Distributor Take Back Scheme
ECM	:	Environmentally Conscious Manufacturing
ECO^2	:	Ecological and Economical
ELV	:	End-of-Life Vehicles
EoL	:	End-of-Life
EPR	:	Extended Producer Responsibility
LCA	:	Life Cycle Assessment
LCD	:	Liquid Crystal Display
PCB	:	Printed Circuit Board
PCS	:	Producer Compliance Scheme
RoHS	:	Restriction of certain Hazardous Substances
RPP	:	Recycling Process Planning
WCS	:	Worst Case Scenario
WEEE	:	Waste Electrical and Electronic Equipment

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Chapter 1

Introduction

Throughout the human history, the ecosystem so far has shown a limitless ability to absorb our unwanted materials and to supply us with the resources we require to survive. However, rapid industrialisation has changed all the previous assumptions. There is now a general global consensus among researchers that industrialisation has played its role in many problematic phenomenons like ozone depletion, acid rain, air and water pollution, and more importantly climate change and alarming rates of non renewable resource consumption. Increased awareness towards these global environmental problems has enhanced the need for 'Sustainable Development' through innovation and sustainable engineering solutions. The achievement of such solutions leading to sustainable development necessitates significant changes in the current patterns of over production, wasteful consumption and disposal. Environmental legislations throughout the developed world are attempting to bring these changes. In Europe, extended producer responsibility legislation has taken a proactive stance and has formulated a number of regulatory directives encompassing the design, production, and end-of-life treatment of a range of products.

Waste from Electrical and Electronic Equipment (WEEE) has been identified as one of the fastest growing sources of waste in Europe (Cui and Forssberg 2003). Technological innovation and shorter product life cycles of electrical and electronic equipment coupled with its increasing use in daily life are contributing to this rapid growth (The European Commission 2000b). In Europe (EU 15), 6 million tonnes of WEEE were generated in 1998 (The European Commission 2000b), and the amount of WEEE has expected to increase by 3 – 5% per annum (Snowdon *et al.* 2000). Although a small proportion of this waste (mainly white goods) has been recycled, a large proportion of WEEE which contains potentially recyclable material is being sent to landfills. In addition, WEEE is non-homogenous and complex in terms of materials and components, and includes highly toxic materials which can cause serious environmental and health problems during disposal if not pre-treated.

The consumption of scarce materials in the manufacture of electrical and electronic equipment and its disposal in scarce landfill capacity along with environmental and health problems caused by WEEE have raised concerns among the governments, environmentalists, manufacturers and consumers. As a result, European Commission introduced the WEEE Directive requiring producers to take responsibility for the waste management of their products. The scope of this producer responsibility directive targets manufacturers, distributors, consumers, and all parties involved in the treatment of WEEE and it aims to reduce the amount of WEEE going to landfills, increase reuse, recycling, and other forms of recovery in order to reduce the environmental impacts associated with the End-of-Life (EoL) phase of electrical and electronic equipment (The European Commission 2003c). In its simplest sense the directive requires manufacturers to finance collection, treatment, and recycling and recovery of separately collected WEEE to the specific treatment standards and meet recovery and recycling targets of 50-80% by weight depending on the type of product.

Historically in the UK, the metal dominated products (white goods) have mainly been targeted for recycling which are often processed together with other metallic streams (e.g. automobiles) to recover the ferrous metals. Such recycling activities have primarily been undertaken for commercial reasons to obtain the value from secondary metals without any consideration to the environmental impact of substantial quantities of waste being sent to landfill sites without any treatment. The appropriate recovery and recycling of WEEE has the potential to substantially improve the sustainability of electrical and electronic equipment through resource conservation and waste minimisation. Yet at present, the majority of manufacturers and commercial end-users do not consider the operations involved in EoL treatment as their core business, and therefore outsource the EoL management of their products. In the UK, many electrical and electronic equipment manufacturers have followed this trend and opted to conform to the WEEE directive by moving away from actively fulfilling the requirements themselves, in favour of utilising the producer compliance schemes. Producer compliance schemes dispose their member's recovery and recycling obligations through WEEE recovery facilities. These recovery facilities are often developed on an ad hoc basis and mainly due to the hidden economic value within the used products. Furthermore, the recovery treatment of WEEE is mainly based on the capabilities and available resources within these electrical and electronic equipment recovery facilities,

without any detailed assessment of the environmental benefits of such recycling activities. However, at present the recycling facilities are faced with the challenge to improve WEEE recycling activities to ensure that a larger proportion of components and materials are being recovered at a reasonable cost and yet at the same time legislative requirements are being met.

The research assertion made in this thesis is that to adequately meet the challenges of achieving the legislative requirements and long-term sustainability, WEEE recovery sector needs greater consistency together with detailed understanding about the best course of recovery action for individual products to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable environmental and economical cost. This highlights the need for a systematic approach to aid the decision making involved in selecting the best possible EoL strategies for individual products in WEEE. Therefore, the research reported in this thesis has proposed a novel recycling process planning framework to determine the most suitable EoL options for WEEE. It is envisaged that the adoption of such a systematical approach to the generation of bespoke recycling process plans for various products is essential to address the issues hindering the current end-of-life treatment, and can significantly improve the 'value recovery' and environmental performance of WEEE recycling practices.

The overall aim of the thesis is therefore to promote sustainable practices within WEEE recovery industry through the application of a recycling process planning framework, and to generate environmentally friendly and economically justifiable recycling process plans for individual products in WEEE.

The research issues addressed in this thesis are,

- The generation of an EoL model for WEEE recycling encompassing various sources of waste creation, disposal routes and recycling options to establish the current state-of-art.
- The design and specification of a novel recycling process planning framework to generate bespoked recycling process plans for individual products in WEEE.
- The investigation of the ecological and economical impacts associated with various EoL options for WEEE.

The structure of this thesis is broken down into three distinct sections; research background and overview, theoretical and experimental research, and research conclusions, as illustrated by Figure 1.1.

The research background and overview section consists of the initial five chapters and provides an introduction to a range of issues regarding WEEE recovery, the research assertion, research aims, objectives and scope as well as a review of related research publications and background knowledge to the research. Chapter 1 introduces the subject and provides the layout of the thesis. Chapter 2 outlines the context of the research and contains the research objectives together with a description of the scope of the research. Chapter 3 introduces the current WEEE recovery sector and the main stakeholders, recycling activities, and the relevant environmental legislations. Chapter 4 reviews the most relevant waste management and product recovery research related to WEEE recycling. This section is completed by chapter 5 which presents an overview of different approaches to process planning.

The theoretical and experimental research section consists of five chapters which establish the research methodology, generate an integrated recycling process planning framework, devise an ecological and economical assessment approach, design and specify a computer aided recycling process planning system and then demonstrate the application of recycling process planning framework using a number of case studies. Chapter 6 outlines the research methodology used in this thesis. Chapter 7 describes an integrated recycling process planning framework to generate eco-efficient recycling process plans for individual products in WEEE. Chapter 8 describe the ecological and economical assessment methodology, which is part of the integrated recycling process planning framework, and calculates the impacts associated with various end-of-life options for WEEE. Chapter 9 presents the design and specification of the computer aided recycling process planning system. Chapter 10 highlights suitable case studies to demonstrate the effectiveness of the proposed recycling process planning framework.

The final two chapters of the thesis contain the research conclusions. A critique of the theoretical and experimental research is conducted in the research discussion in chapter 11. Finally, chapter 12 concludes the thesis by identifying a number of research conclusions and identifying further work for the continuation of this research.

In addition, *Appendix 1, 2 and 4* provides related published and accepted papers by the author on various aspects of the research reported in this thesis. *Appendix 3* provides a background to the Eco-indicator methodology which is used to calculate the environmental impacts of WEEE recovery and recycling activities in this thesis. *Appendix 5* provides the additional information about the case studies conducted in this research.

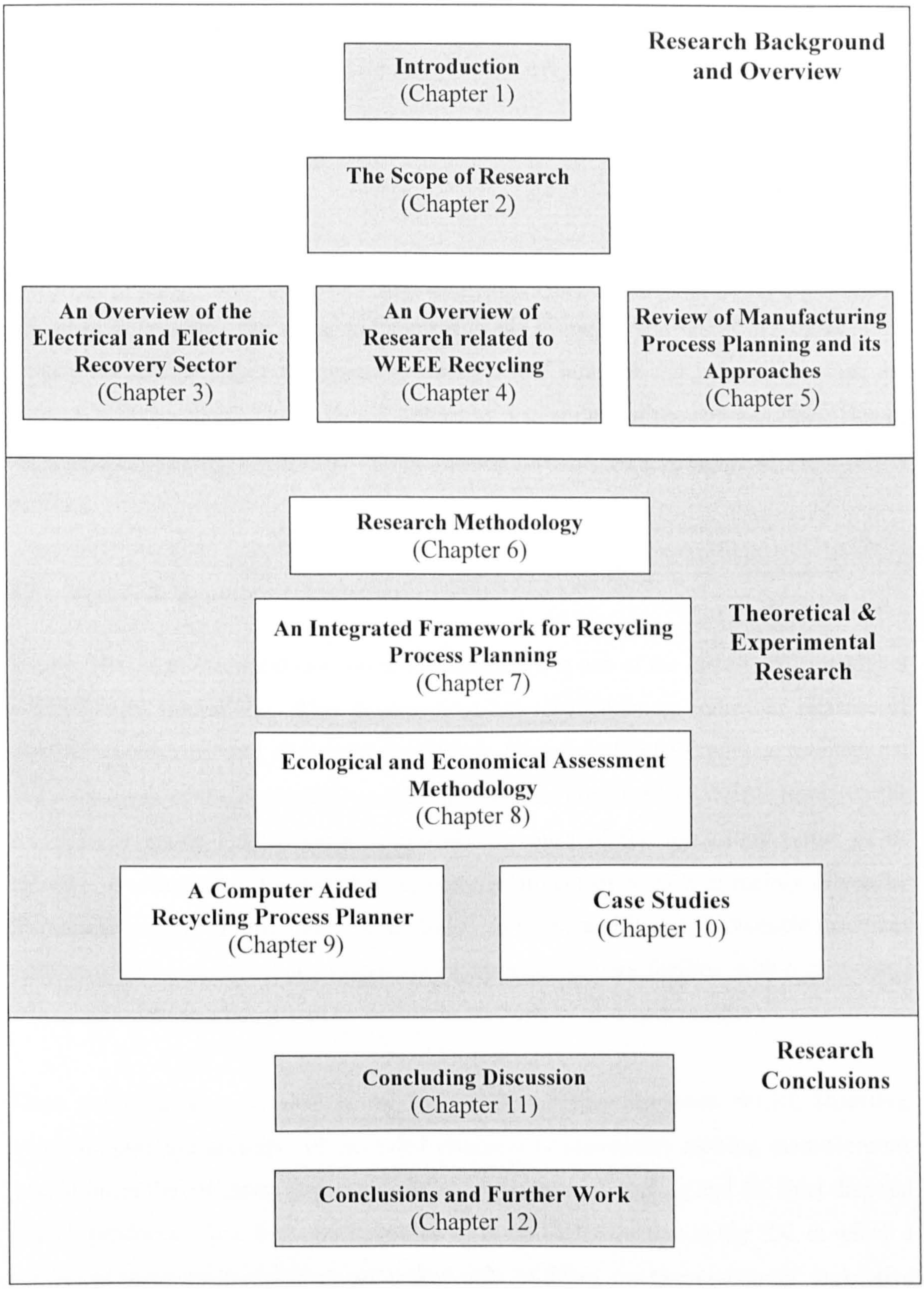


Figure 1.1: Thesis structure

Chapter 2

The Scope of Research

2.1 Introduction

This chapter describes the scope and context of the research reported in this thesis. The opening section describes the research assertion and includes the context in which the research is undertaken. This is then followed by a statement of the aim and objectives of the research. Finally, the specific scope formed to meet the objectives of the thesis is outlined.

2.2 Research Hypothesis/Assertion

The production of electrical and electronic equipment is one of the fastest growing global manufacturing operations. This development has resulted in an enormous increase of waste from electrical and electronic equipment. Disposal of WEEE poses a problem not only as a result of the potentially recyclable materials contained in WEEE filling up the increasingly scarce landfill capacity but also because of the hazardous nature of its contents. Furthermore, the existing recovery treatment of WEEE is mainly driven by economical considerations and typically based on the capabilities and available resources within a specific electrical and electronic equipment recovery facility, with a substantial amount of waste still being sent to landfill in the form of shredder residue.

These concerns have resulted in the introduction of the European WEEE Directive, which follows the principal of extended producer responsibility making manufacturers (and at times the retailers) responsible for the take-back, recycling and the final disposal of their products. Due to the transposition of the WEEE directive in the UK, in which a number of recovery consortiums are tasked with fulfilling the manufacturers' legislative requirements, the recovery and recycling of WEEE is undertaken by industry with little understanding of the products they are recovering. The complexity of materials contained within each product and the huge variety of products in electrical and electronic equipment (ten categories of electrical and electronic equipment under WEEE

directive), make ad hoc applications of WEEE recycling highly ineffective in terms of both ecological and economical considerations. In addition, the complexity of materials contained in WEEE does not allow a generic EoL option to be used for different products and requires initial processing and customisation of EoL recycling strategies for individual electrical and electronic products.

The author argues that the current ad hoc approaches to WEEE recycling will not provide the long-term solutions for environmentally friendly and economically justifiable recovery activities in this sector. Furthermore, one of the recent trend in electrical and electronic products has been the reduction of the amount of precious metals (gold, palladium, silver etc.) contained in them to reduce the manufacturing cost. The recovery of these precious metals has been one of the main economic motivations in current electrical and electronic equipment recovery and recycling practices. This further highlights the need to improve the environmental and economical performance of WEEE recovery activities to ensure long-term sustainability of electrical and electronic recovery sector.

Following a review of current practices and published research in this area (reported in chapters 3 – 5), the research assertion made in this thesis is that there is a need for a systematic and a more efficient recycling approach which addresses the current shortcomings of the recovery sector to effectively maximise the recyclability of WEEE and minimise the environmental and economical impacts of its recovery and disposal. Hence, the research hypothesis is that by providing an appropriate recycling planning approach together with a bespoke end-of-life decision support mechanism assessing the environmental and economical impacts of different recovery and recycling activities, it is possible to improve the end-of-life performance and legislative compliance of WEEE recovery sector.

2.3 Research Aims and Objectives

Following a review of current WEEE recycling practices and published research in this area, the overall aim of this research is defined as the promotion of sustainable practices within WEEE recovery industry through the generation of new knowledge related to environmentally friendly and economically justifiable recycling of electrical and electronic equipment, by generating:

i. An end-of-life model encompassing various sources of waste creation, disposal routes and recycling options to establish the current state-of-art,
ii. An integrated framework and an associated computer aided recycling process planner to support the planning of recycling activities and to generate eco-efficient recycling process plans,
iii. An assessment methodology to calculate the ecological and economical impacts associated with various EoL options for WEEE.

To achieve this aim and based on the shortcomings identified in literature and existing practices, the major research objectives are defined as follows:

a) To review the relevant research work and the state-of-art in WEEE recovery and recycling, waste management, and process planning.

b) To construct an end-of-life model for WEEE recovery based on the results of the background review and a survey of industrial practices.

c) To generate a novel framework to support the recycling process planning for WEEE.

d) To devise an integrated ecological and economical assessment methodology to effectively cost the environmental and economical impacts of WEEE recycling processes.

e) To design and implement a novel computer aided recycling process planner which can generate bespoke eco-efficient recycling process plans for WEEE.

f) To demonstrate the application of the recycling process planner through a number of case studies.

2.4 Scope of Research

The scope of this research is in line with the research objectives and is listed below. A short description of each of these follows in sections 2.4.1 to 2.4.6.

i. Review existing literature on environmentally conscious manufacturing, waste management and product recovery of WEEE, and process planning,
ii. Produce an end-of-life model for WEEE recovery,
iii. Generate a novel recycling process planning framework,
iv. Devise an integrated ecological and economical assessment methodology,
v. Produce a prototype computer aided recycling process planner,
vi. Validate the recycling process planning framework and the associated recycling process planner via a number of case studies.

2.4.1 Review Existing Literature on WEEE Recovery and Recycling

In order to effectively place the research within the appropriate academic context, and to take the advantage of the existing knowledge, an extensive review of the literature in the fields of environmentally conscious manufacturing, product recovery, waste management, and process planning will be undertaken. Parallel to the literature study, a critique of the existing methodologies supporting WEEE recovery will be presented.

2.4.2 Produce an End-of-Life Model for WEEE Recovery

An extensive review of current waste arising together with reuse, recycling and disposal practices in the electrical and electronic equipment recovery sector shall be undertaken to effectively reflect the current and future end-of-life WEEE processing. This is to include interviews with various stakeholders in WEEE recovery chain, an evaluation of WEEE recovery routes, and an appraisal of literature considering present and future recovery technologies. The results of this investigation will be summarised in the end-of-life model which effectively summarise the various sources of waste creation, disposal routes and various recycling options available for WEEE.

2.4.3 Generate a Novel Recycling Process Planning Framework

The identification of various tasks involved in the recycling process planning to determine the appropriate end-of-life treatment for WEEE forms the basis of the framework development. This framework aims to assist designers, manufacturers, and electrical and electronic equipment recycling facilities in determining the bespoked end-of-life recycling process route for an individual product in WEEE, and therefore provides a structured approach to reduce the overall impact of conflicting environmental and economical impacts in WEEE recycling. In addition, the framework further extends previous research in EoL decision support systems by considering optimal sets of trade-offs between environmental and economical variables and includes simultaneous consideration of the macro level and micro level end-of-life planning.

2.4.4 Devise an Integrated Ecological and Economical Assessment Methodology

A key problem in the end-of-life management of WEEE is to determine to what extent used products must be disassembled and which end-of-life option should be applied while minimising the environmental and economical impacts of product recycling. Hence, there is a need for an assessment method to assess the impacts of various end-of-life options in order to select the appropriate end-of-life option for a product under consideration. This research will design and specify one such assessment method to evaluate the ecological and economical impacts involved in WEEE recycling through the application of Eco-indicator 99 methodology and cost-benefit analysis respectively.

2.4.5 Produce a Prototype Computer Aided Recycling Process Planner

The generation of eco-efficient recycling process plans for WEEE is a complex task which involves concurrent consideration of product and process data related to a wide range of end-of-life issues such as varying material composition, weight and product structure, product age and condition, and various recycling processes and technologies together with their environmental and economical impacts. Therefore, this research will design and implement a prototype computer aided recycling process planner based on the various tasks included in the recycling process planning framework.

2.4.6 *Demonstrate the Application of the Framework*

In order to assess the validity and applicability of the proposed recycling process planning approach and its associated ecological and economical assessment, a number of related case studies will be undertaken. Industrial and experimental data will be used to calculate the ecological and economical impacts associated with WEEE recycling. The results of these case studies will be used to highlight the potential improvements in WEEE recycling. This will provide a benchmark against which the suitability of various end-of-life options for WEEE can be measured.

Chapter 3

An Overview of the Electrical and Electronic Recovery Sector

3.1 Introduction

This chapter provides an overview of the current activities in electrical and electronic recovery sector within the UK, and its changing status based on the implementation of the WEEE directive. In addition, the chapter provides an indication of current shortcomings encountered within the recovery sector, and factors that are most relevant to effective end-of-life management of WEEE. The chapter begins by describing the quantities of WEEE arising and current electrical and electronic recovery practices. Legislative drivers and restrictions associated with WEEE are then presented along with their implementation in the UK. Finally, the implications of the legislation on electrical and electronic recovery sector operators are described in detail.

3.2 Waste Arising and Recovery Practices for WEEE

Electrical and electronic equipment has infiltrated every aspect of our lives, providing our society with more comfort, health and security. On the other hand, beneath the glamorous surface of the benefits and the wealth created by the electrical and electronic equipment looms a darker reality. Vast resource consumption and waste generation are increasing at alarming rates. The production of electrical and electronic equipment is increasing worldwide, and as a consequence of this growth, combined with rapid product obsolescence and a growing consumerism, discarded electrical and electronic equipment or WEEE, has become one of the fastest growing waste stream in the world (see Figure 3.1). It had been predicted that 7.3 million tonnes of WEEE was created in Europe in 2002 (Hesselbach *et al.* 2001). Studies conducted in Europe estimate that the quantity of WEEE is increasing by 3% - 5% per year which is three times faster than the increase in municipal waste stream (Snowdon *et al.* 2000; Turbini *et al.* 2001; Alec 2002). Even then until recently a larger proportion of this waste was being sent to landfills.

Figure 3.1: Waste from electrical and electronic equipment

Disposal of WEEE poses a problem not only as a result of the potentially recyclable materials contained in WEEE filling up the increasingly scarce landfill capacity but also because of the hazardous nature of its contents. WEEE should not be destined for landfill or incineration with unsorted municipal waste as it contains a variety of different hazardous substances such as lead and cadmium in circuit boards; lead oxide and cadmium in monitor Cathode Ray Tubes (CRTs); mercury in switches and flat screen monitors; cadmium in computer batteries; polychlorinated biphenyls in older capacitors and transformers; and brominated flame retardants on printed circuit boards, plastic casings and cables. Recovery processes using incineration may also lead to hazardous emissions due to the presence of heavy metals in the WEEE. The danger in landfilling WEEE lies in the leaching of hazardous substances, as no landfill site is completely watertight, resulting in soil and groundwater contamination. Some of the potential damages for the human health and the environment from the toxic substances commonly found in WEEE are outlined in Table 3.1 (The European Commission 2000b).

Hazardous Materials	**Potential damages for human health**	**Potential damages for the environment**
Lead (Pb)	Can damage the nervous systems, the endocrine and cardiovascular systems, and the kidneys	Lead accumulates in the environment and has high acute and chronic effects on plants, animals and micro-organisms
Cadmium (Cd)	Can have irreversible effects on the kidneys, provoke cancers or induce skeletal demineralisation.	Bio accumulative, persistent and toxic for the environment
Chromium VI	Can cause allergic reactions, is caustic when in contact with the skin, and genotoxic as well	Easily absorbed into cells, with toxic effects
Mercury (Hg)	Can cause damage to various organs including the brain and kidneys, as well as the fetus	Spread in the water, is accumulated by living organisms
Brominated flame retardants (BFR)	Cancerogenic and neurotoxic, they may also have negative effects on reproduction	Soluble in landfill leachates, bio accumulative, their incineration may lead to the generation of dioxins and furans
Nickel (Ni)	Can affect the endocrine and immune systems, the skin, and the eyes	

Table 3.1: Adverse effects of the hazardous substances included in WEEE

3.2.1 WEEE Arising in the UK

The growing quantity of WEEE is beginning to reach disastrous proportions and industrialised countries all over the world are now beginning to tackle with the problem. In Europe, end-of-life product take back legislation for electrical and electronic equipment (namely the WEEE directive) aims to improve the recovery and recycling of a range of products (see section 3.6). In the WEEE directive, all electrical and electronic equipment has been grouped into one of ten categories. A report compiled by Industry Council of Electronic Equipment Recycling (ICER) based on the sales data from 2003 highlights the contribution of individual categories of equipment towards the total WEEE arising in the UK, as summarised in Table 3.2. ICER's estimate to the total quantity of WEEE arising in the UK is 940K tonnes per year (ICER 2005). Large household appliances make the largest contribution (69%) towards the weight of household WEEE, whereas in terms of number of appliances discarded small household appliances make the largest contribution (31%).

In addition to the variation in weights and numbers towards the total waste, different categories of electrical and electronic equipment have different material compositions. For example, large household appliances consist mainly of steel (at around 61% of mass on average), whereas consumer electronic products consist largely of glass, ceramics, and plastics (at around 65% of mass on average).

Categories of WEEE	Tonnage discarded Tonnes (x 1000)	Per cent (Total Weight)	Units discarded (millions)	Per cent (No. of Units)
Large household appliances	644	69	14	16
Small household appliances	80	8	30	31
IT/Telecommunication equipment	68	7	21	23
Consumer equipment	120	13	12	13
Tools	23	2	5	5
Toys, leisure and sports equipment	2	<1	2	2
Lighting	2	<1	9	10
Monitoring and control equipment	<1	<1	<1	<1
Total	940	100	93	100

Table 3.2: Arising of domestic WEEE in the UK (ICER 2005)

The material composition of different appliances within the same category can also vary substantially. For example in consumer equipment category, hi-fi equipment does not usually contain the glass or wood contained in the cathode ray tubes and casings of televisions; or in the case of white goods, fridges and freezers do not usually contain the concrete contained as a balancing counter-weight in washing machines. Table 3.3 highlights the material composition of various categories of electrical and electronic equipment (Hedemalm *et al.* 1995).

It is therefore argued that due to this variety of materials mix and the range of routes through which WEEE may be discarded; the recycling of WEEE is more complex than the recycling of conventional materials and products such as steel, aluminum, paper and vehicles. In addition, the complexity of materials contained in WEEE does not allow a generic end-of-life option to be used for different products and requires careful consideration of end-of-life recycling strategies for individual electrical and electronic equipment products.

	Iron (%)	Copper (%)	Other metals (%)	Glass ceramics (%)	Plastic with flame retard	Plastic without flame retard	Liquid wood paper (%)
Home kitchen appliances	25	6	9	10		50	
Large domestic appliances	63	5	2	12		18	
Other electrical home appliances	60	3	2		35		
Toys and musical instruments	20	2	3		10	65	
Electrical tools	30	10	10	20	15	15	
Consumer electronics	10	5	2	30	15	38	5
Electrical lighting equipment	7	7	3	83			
Office electrical equipment	30	10	10	20	15	15	
Radio and telecommunications	55	10	5		15	15	
Control, regulation and surveill	55	10	5		15	15	
Medical equipment	55	10	5		15	15	
Industrial installations	95	1		2	1	1	

Table 3.3: Differences in composition of WEEE (Hedemalm *et al.* 1995)

3.3 An End-of-Life Model for Waste from Electrical and Electronic Equipment

Electrical and electronic equipment is typically divided into large household appliances, Information Technology (IT) equipment, consumer equipment, and small electrical appliances. Currently, large appliances are mainly collected together with scrap metals at the municipal collection centres. After dismantling and removal of poly chlorinated biphenyl capacitors, and mercury containing components (switches), this fraction is added to scrap metals and mechanically separated in shredding facilities. IT equipment and appliances with cathode ray tube are gathered separately and dismantled. Casings (plastic and partly wood) are separated and presently still landfilled. Hazardous components such as large capacitors and buffer batteries and accumulators as well as Liquid Crystal Displays (LCDs) are removed and specially treated as hazardous waste. Small electrical appliances are at first submitted to the removal of hazardous components (for instance switches and relays containing mercury, polychlorinated biphenyl capacitors, batteries, etc.) and these parts are forwarded to specific treatment options according to the special type of pollutant.

The appliances of which the hazardous fractions are removed are mechanically processed. By this treatment procedure mainly the metal-containing fraction is recovered. The remaining fraction, containing mainly plastic, is thermally treated or landfilled. As WEEE is a mixture of various materials, it can be regarded as a resource of metals, such as copper, aluminium, gold, and plastics. The complexity of materials contained within each product and the huge variety of products in electrical and electronic equipment make ad hoc applications of WEEE recycling highly ineffective in terms of both ecology and economy. The review of these EoL activities within different recovery and recycling facilities has highlighted that there is little consistency regarding WEEE recycling owing to lack of formal procedures to determine the best course of action for individual products. However, to recycle a wide range of different types of electrical and electronic products, the development of new technologies, tools and infrastructure has now become essential. A model encompassing different activities in end-of-life management of WEEE is presented in Figure 3.2.

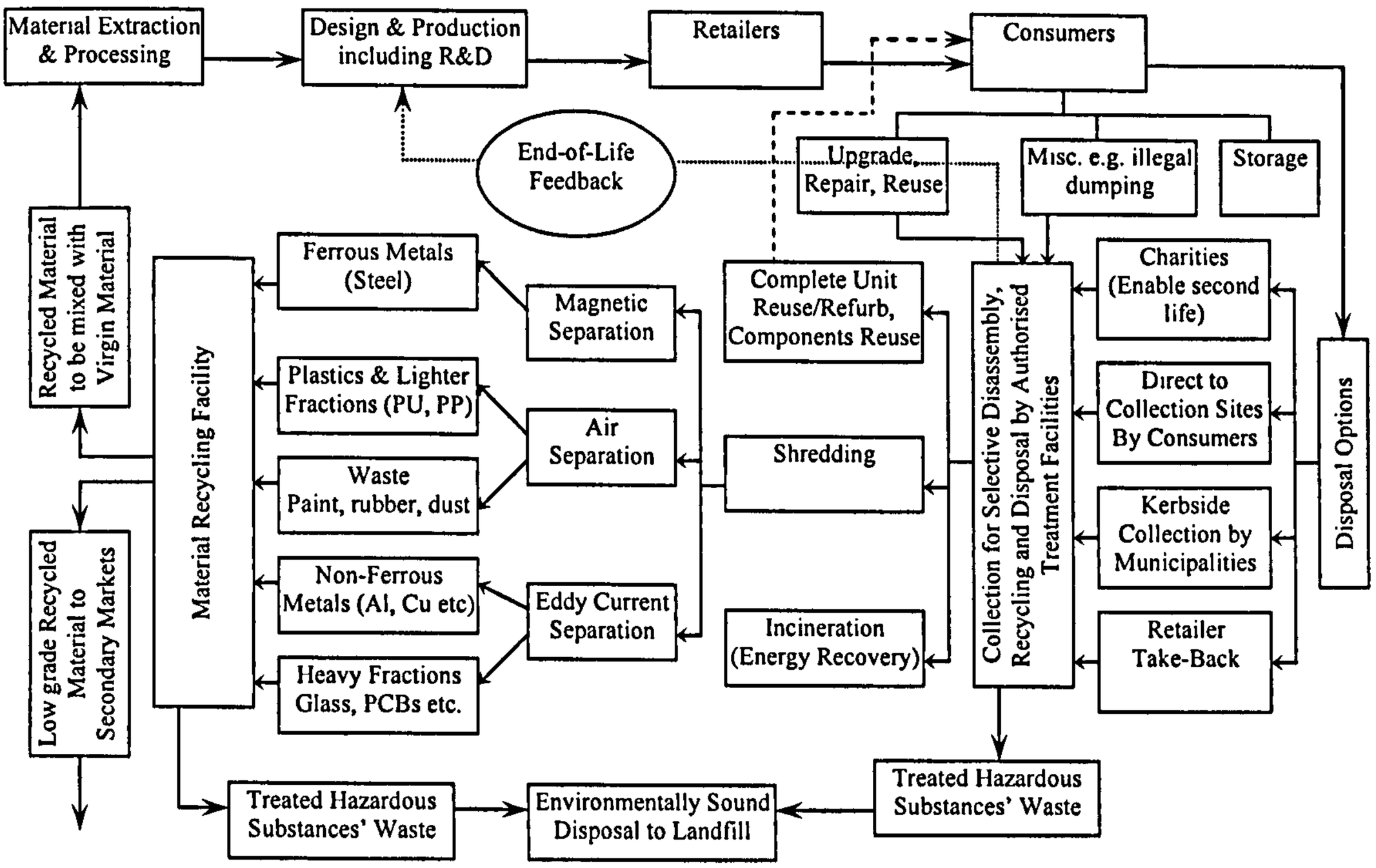


Figure 3.2: An end-of-life model for waste from electrical and electronic equipment

The generation of the end-of-life model, encompassing various sources of waste creation, disposal routes and recycling options available for WEEE, is the first step towards building an integrated recycling process planning framework to support the EoL management of WEEE. An overview of this end-of-life model is also provided in Bakar and Rahimifard (2007b) (see *Appendix 1*). Recycling of WEEE is an important step in the overall management of WEEE. With the steadily decreasing precious metal content included in electrical and electronic equipment, manual dismantling and treatment is increasingly becoming economically unviable. Mechanical recycling of WEEE is gaining increasing attention to replace the costly recovery and recycling techniques (hydrometallurgy, pyrometallurgy) once applied to electrical and electronic equipment (Zhang and Forssberg 1997). Mechanical recycling can be broadly divided into three major stages, namely disassembly, upgrading and refining (Cui and Forssberg 2003). Disassembly and upgrading of WEEE are described in more detail in the following sections.

3.3.1 Disassembly/Dismantling

Most recovery and recycling facilities utilise manual sorting and disassembly. This is a major cost element within any recycling methodology. Dismantling mainly involves the removal of hazardous materials and components such as batteries and other items

prescribed by the WEEE directive. Disassembly is a systematic process that allows the removal of a component, part, group of parts or a sub-assembly from a product (partial disassembly) or the separation of a product into all of its component parts (complete disassembly) for a defined purpose. Complete disassembly of a product is, in almost all cases, economically unviable, whereas, partial disassembly can improve the environmental and economical performance of product recycling

3.3.2 Upgrading/Shredding

Electrical and electronic waste contains valuable metals such as steel, copper, aluminum, and gold. After disassembly and dismantling, most of the fractions in WEEE are processed in mechanical recycling processes in which the valuable metals, plastics or other substances are separated from the product hulk. The first step in the upgrading of WEEE typically involves shredding for size reduction. Only when the disassembled WEEE is transformed to proper granularity, can the materials included in WEEE be separated. The term 'shredding' is used to describe size reduction by impacting, shearing, grinding, milling and pulverizing. The high metal content in many scrap feeds requires the use of shearing forces for size reduction, a prime example being fragmentisers used for scrap automobile processing. The size of an auto shredder, which are also being used for processing WEEE, can range from 1000 to 7000 horse power, and process up to 200 tonnes of feedstock per hour (Ambrose *et al.* 2000).

After liberation of the materials in the disassembled WEEE through shredding, their separation is performed by mechanical/physical methods. All of the post-fragmentation separation processes used for physical separation of components are based on the principle of coding and separation. A particular property of the material is used as a recognition code, such as magnetic/non-magnetic or large/small. Once coded, the material is separated according to the code. In screening, for example, the small particles fall through the screen and large ones are retained. Mechanical separation of WEEE is based on the different properties of the existing materials in the different end of life products. The properties which can be utilised in separation processes are based mainly on the differences in size and/or shape, specific density, magnetic properties, electrostatic properties, and electrical conductivity. The separation processes used for WEEE are described in the following sections.

3.3.2.1 Air Separation

The process of air separation generally exists in two stages, the first where the light materials are separated from the heavy materials by an air current, and the second where the light materials are separated from the air usually via a cyclone (Vesilind and Rimer 1981). This initial separation is reliant on several of the materials' properties including density and area. Shredder operators usually implement air separation immediately after shredding, leaving a large metallic rich heavy fraction and a small highly mixed light fraction consisting of materials such as plastic, foam, and textiles.

3.3.2.2 Size Separation

Size separation or screening separates particles by size either via a trommel or a reciprocating screen. The primary method of screening in metals recovery uses the rotating screen, or trommel. These screens have a high resistance to blinding which is important because of the large range of particle shapes and sizes encountered in wastes. Vibratory screening is also used, but can be inefficient in case of WEEE that contain wire, due to entanglement and subsequent blinding of the screening deck (Veasey *et al.* 1993).

3.3.2.3 Magnetic Separation

Magnetic separation is achieved by passing the material flow under the influence of a changing magnetic field. Differences in magnetic susceptibility can be used to effect separation of different materials. Coding occurs when the ferromagnetic component interacts with a magnetic field and separation is by magnetic attraction. Low-intensity drum separators or overband machines are used widely for ferrous recovery, and the general categories of use are either for purification of feed streams containing unwanted magnetic impurities or for the concentration of magnetic materials. In most recovery and recycling applications, magnetic separation is used for the recovery of ferromagnetic metals (ferrous) from non-ferrous metals and other non-magnetic wastes.

3.3.2.4 Eddy-current Separation

One of the most significant developments in metals recovery and recycling has been the introduction of eddy-current separators based on the use of rare earth permanent

magnets. The separation forces imparted by an eddy-current separator are a function of the magnetic field intensity and the alternating frequency of the magnetic field. Eddy-current separation is a process based on the forces of magnetic repulsion. This is achieved by inducing eddy currents in conductors creating repulsion to the magnetic field present (see Figure 3.3). Eddy-current separation is particularly suited to the separation of metals from most non-metals. The separators were initially developed to recover non-ferrous metals from shredded automobile scrap or for treatment of municipal solid waste to recover aluminium, but the range of application is now very wide and includes electronic scrap and glass cullet (crushed light bulbs).

3.3.2.5 Dense Media Separation

Separation by density divides a material stream by whether the content sinks or floats in a particular liquid medium. The separation is therefore dependant on the comparative densities of the medium and the material content of the stream. A variety of methods are employed to separate the heavier from the lighter materials. The most common non-ferrous metals recovery process is the sink–float or heavy-medium method. This separation is usually employed to treat non-magnetic residues from a number of fragmentiser operations. Drum separators are commonly used in End-of-Life Vehicle (ELV) recovery and involve a rotating cylinder which picks up the sink materials from the bottom, whilst the floats move with the flow of the medium.

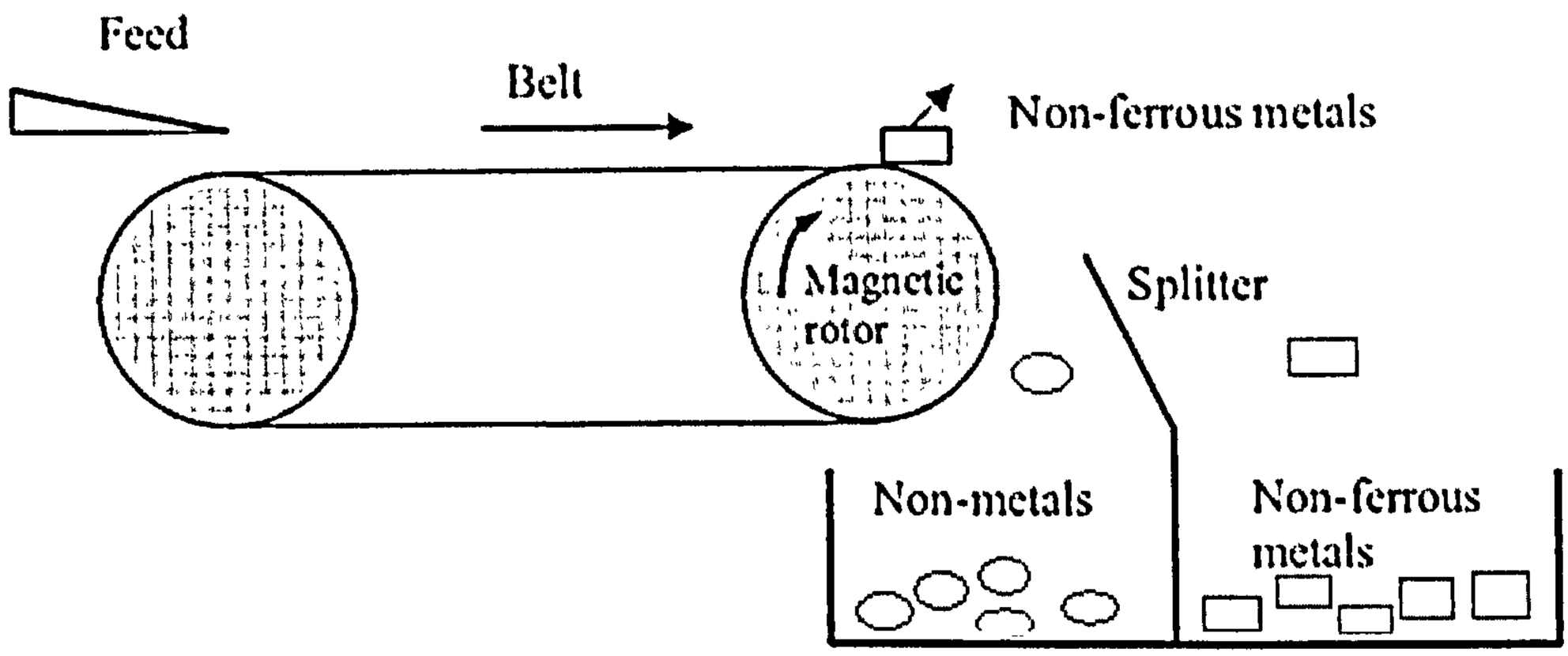


Figure 3.3: Separation principle of an eddy-current separation device (Zhang and Forssberg 1997)

3.4 Environmental Legislation related to Electrical and Electronic Sector

Much of the UK's waste legislation has been developed in relation to European directives. European Union (EU) legislation accounts for an estimated 80% of UK environmental regulations (Lowe and Ward 1998). These directives come in three forms, horizontal legislation creating frameworks for the management of waste and future directives, treatment legislation which restricts and controls specific operations within the waste industry, and waste stream legislation which exerts influence on the life cycle of a specific product in order to reduce or reform its disposal to landfill. Directives that have been produced within these three legislative forms, and are related to WEEE are shown in Figure 3.4 along with their equivalent UK transpositions. All the directives have the philosophy of Extended Producer Responsibility (EPR) at their core, which aims to promote end-of-life considerations within the product design process, and the reduction of a product's overall ecological impact. Toffel (2002) refers to the justification of the manufacturers as being the focus for EPR due to the "critical leverage point" it has in terms of product design. The following sections outline each European directive and resulting UK legislation within each of these three categories.

3.4.1 Horizontal Legislation

Both the Directive on Waste and the Directive on Hazardous Waste provide a framework for waste management uniformity across the EU in all sectors for all waste types. The original Directive on Waste of 1975 (The European Commission 1975) and its successor of 2006 (The European Commission 2006) attempt to:

- Ensure the protection of human health and the environment
- Define waste types and terminology
- Encourage recovery in order to conserve natural resources
- Promote clean technologies and products that can be reused and recycled

With relevance to WEEE, the directive on waste established producer responsibility, via polluter pays principle, as a central pillar of future European waste legislation. Much of the resulting UK legislation has been to license those who treat, keep, deposit or dispose off waste through the Environment Agency.

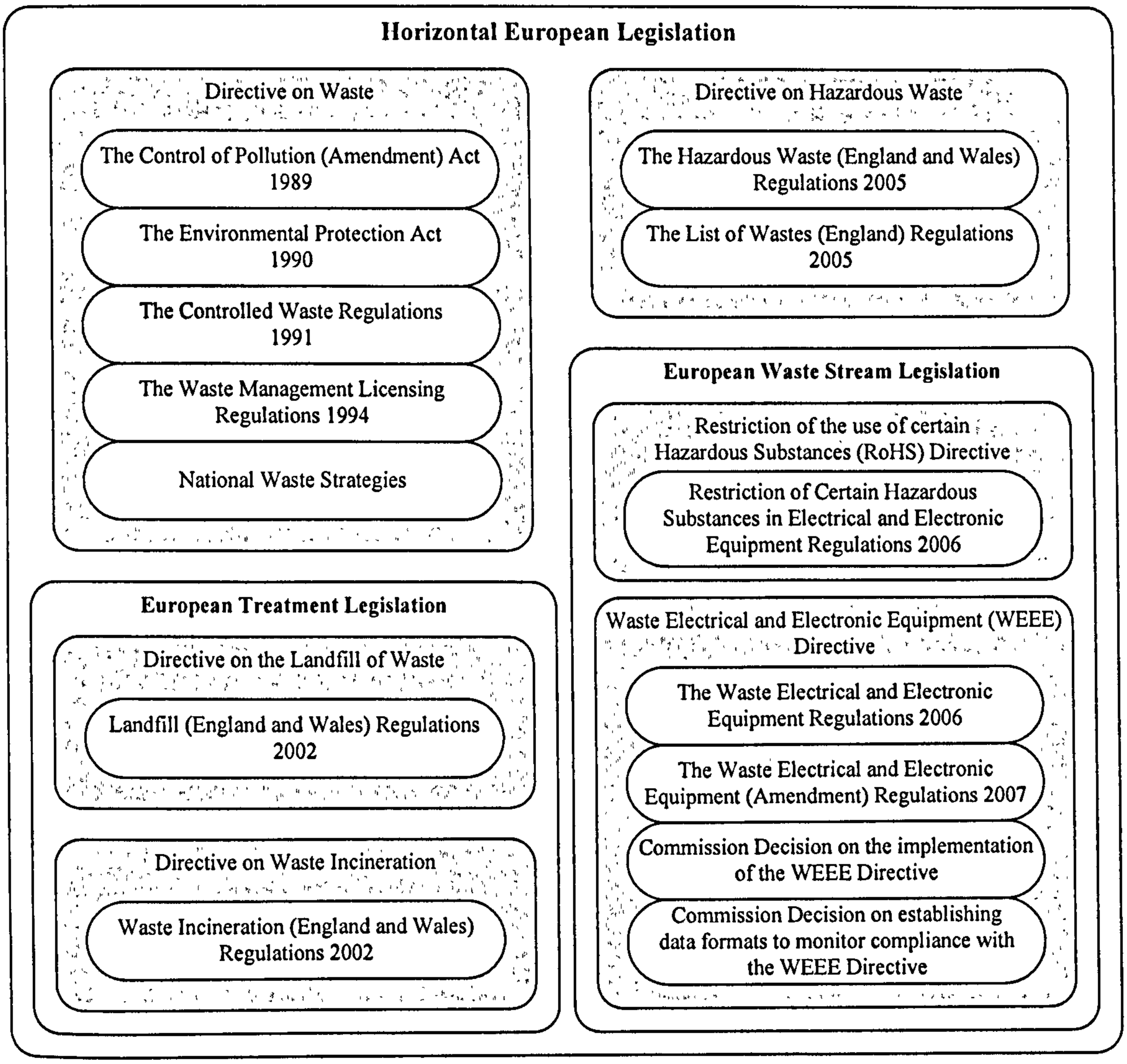


Figure 3.4: European and UK waste legislation surrounding WEEE

Whilst the Directive on Waste attempted to distinguish recovery from disposal, the Directive on Hazardous Waste of 1991 (The European Commission 1991) defined hazardous and non-hazardous waste and in turn, made the management and monitoring of hazardous waste more stringent. The UK transposition was consolidated in 2005 into two parts, the Hazardous Waste Regulations (UK Government 2005a) which established the control of hazardous substances and the List of Waste Regulation (UK Government 2005b) which defined hazardous waste types.

3.4.2 Treatment Legislation

The European Directive on the Landfill of Waste (The European Commission 1999) came into force in 1999 and aims to improve standards of landfilling across Europe, by

setting specific requirements for the design, operation and aftercare of landfills, and for the types of waste that can be accepted at landfill sites. Targets were set to reduce the landfilling of biodegradable material to 75% by 2006, 50% by 2009 and 35% by 2016, based on 1995 levels. Specific substances were also banned from landfill. This directive resulted in The Landfill (England and Wales) Regulations 2002 (UK Government 2002a), which requires landfill operators to test waste before accepting it as non-hazardous. If waste is found to be hazardous, it can only be landfilled in hazardous waste sites. The Directive on the Incineration of Waste (The European Commission 2000a) aims to prevent, or limit, negative effects on the environment form incineration, in particular pollution of air, soil, surface water and groundwater, and the resulting risks to human health. Waste incineration directive, unlike the landfill directive, has no prescriptive targets. It does however set limits on emissions, operating conditions and water discharge, and strict controls on permits and monitoring. This directive was transposed into UK law in 2002 with the Waste Incineration Regulations (UK Government 2002b).

3.4.3 Waste Stream Legislation

The over-exploitation of scarce materials in the manufacture of electrical and electronic equipment and its dumping into scarce landfill capacity along with the environmental problems caused by electrical and electronic equipment waste has resulted in the introduction of the European WEEE Directive. Parallel to the WEEE Directive, the Directive on the Restriction of Hazardous Substances (RoHS), aims to restrict the use of hazardous substances in electrical and electronic equipment in order to contribute to the environmentally sound recovery and disposal of such wastes. Each of these waste stream legislation and their implementation in the UK is described in the following sections.

3.5 The Restriction of use of Certain Hazardous Substances Directive

The RoHS directive (The European Commission 2003b) came into force in 2003 and aims to restrict the use of hazardous substances in electrical and electronic equipment in order to contribute to the environmentally sound recovery and disposal of such wastes. The directive requires producers of electrical and electronic equipment to ensure that

products they place on the European market *from* 1st July 2006 do not contain hazardous substances such as lead, mercury, cadmium, hexavalent chromium and certain brominated flame retardants (polybrominated biphenyls 'PBB' and poybrominated diphenyl ethers 'PBDE') even if manufactured, imported or already warehoused before that date. The RoHS directive applies to electrical and electronic equipment falling under the scope of WEEE directive (except medical appliances and monitoring and control equipment). There are exceptions for a small number of processes where restricted substances can continue to be used. These cover cases where elimination or substitution of the substances is technically or scientifically impracticable or would have other undesirable impacts. Maximum concentrations are also being agreed at European level (which will allow minimum levels to exist in products).

3.6 Directive on Waste Electrical and Electronic Equipment

The European Directive on Waste Electrical and Electronic Equipment (The European Commission 2003c) came into force in 2003 and aims, as a first priority prevention of WEEE, and in addition increase the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal of waste. Electrical and electronic equipment (*equipment dependant on electric currents or electromagnetic fields in order to work properly and uses a voltage less than 1000V for AC and less than 1500V for DC*) falling into one of the following ten categories is regulated by this directive.

- Large household appliances;
- Small household appliances;
- IT & telecommunications equipment;
- Consumer equipment;
- Lighting equipment;
- Electrical and electronic tools;
- Toys leisure and sports equipment;
- Medical devices;
- Monitoring and control instruments; and
- Automatic dispensers

There are a number of exemptions including: equipment specifically designed for national security or military use; equipment which is only a component of a larger item that does not fall within the scope of the directive (e.g. a CD player built into a car); large-scale stationary industrial tools; implanted and infected medical devices; and filament bulbs.

As the aim of the WEEE directive is to improve the environmental performance of WEEE management, it seeks to achieve this in the following ways:

- ***Eco-design of products:*** Member States are required to encourage the conception and manufacturing of electrical and electronic equipment that facilitates their dismantling and recovery in particular their reuse and recycling, either of the whole appliance, their components or materials (Article 4).

- ***Separate collection of WEEE:*** One of the present restraints to the recycling of the WEEE is insufficient quantities collected to allow large-scale recycling. Members States are required to set up collective collection schemes for WEEE, and encourage the involvement of end-users in these schemes. *By* 2007 all EU countries were set a target of separately collecting household WEEE at the annual rate of 4 kg per inhabitant. If a customer is replacing household WEEE with new equipment of equivalent type the distributor of the new equipment is obliged to take the WEEE (regardless of where it was originally purchased). This can either be in-store or via a distributor compliance scheme. Online vendors are also affected by this requirement (Article 5).

- ***Extended producer responsibility*:** A producer is required to meet the cost of compliance in relation to all household equipment it puts on the market *after* 13 August 2005. In addition producer is required to pay a share of the cost of compliance for the backlog of all historic (i.e. pre 13 August 2005) household WEEE (in proportion to their market share). A different regime applies in relation to non-household equipment. If the equipment was put on the market *after* 13 August 2005 the producer is liable for the costs of compliance. The producer is, however, permitted to pass those costs onto the user. Any non-

household equipment put on the market *before* 13 August 2005 is the responsibility of the user. EU countries have the option to require that the producer meet some or all of the cost of compliance for that historic WEEE if the producer is providing the user with replacement equipment. *From* 13th August 2005 and in order to avoid potential "free-riders" and the problematic financing of the management of their waste, each producer is required to provide a guarantee when placing a product on the market, to ensure the future covering of waste management costs in case the producer disappears from the market. The guarantee may take the form of a recycling insurance, a blocked bank account or a participation in appropriate compliance schemes for the financing of the management of WEEE.

- ***Treatment*:** Separately collected WEEE should be transported to approved treatment facilities unless appliances are reused as a whole. The producers are required to finance the treatment of separately collected WEEE in order to achieve the directive's recovery and recycling rates. WEEE treatment shall as a minimum include the removal of all fluids (substances which could complicate or prevent subsequent recovery or recycling stages), and the selective treatment of some components (Printed circuit board 'PCB', cathode ray tubes, batteries and capacitors, asbestos waste, etc) or substances (mercury, CFC, hydrocarbons, etc) in accordance to the Annex II of the Directive WEEE (Article 6). It is also established in the WEEE directive that any waste exported out of the European Community will only count for the fulfilment of obligations and targets if the exporter can prove that the operations took place under equivalent conditions to the requirements of the WEEE Directive.

- ***Reuse, Recycling and Recovery Targets*:** Article 7 sets recovery and recycling targets rates for the different categories of separately collected WEEE to be achieved by producers, on an individual or collective basis, *by* 31st December 2006. It should be noted that these targets are set to be revised by 2009. Table 3.4 shows the recovery and recycling targets for different categories of WEEE.

Categories of WEEE	Minimum Targets by average weight per appliance	
	Recovery	Recycling and Reuse
Large household appliances	80%	75%
Small household appliances	70%	50%
IT/telecommunication equipment	75%	65%
Consumer equipment	75%	65%
Lighting equipment	70%	50%
Electrical and Electronic tools	70%	50%
Toys, leisure and sports equipment	70%	50%
Medical appliances	No Targets	
Monitoring and control equipment	70%	50%
Automatic dispensers	80%	75%

Table 3.4: Recovery and recycling targets for WEEE

- ***Labelling and product information*:** Producers are required to mark all equipment with a crossed out wheeled bin symbol to indicate that it should not be included in general waste. They are also required to produce technical information to assist treatment, reuse and recycling of the equipment once it becomes waste.

- ***Reporting and enforcement*:** Member states are required to keep a register of producers and collect annual information on the amount of equipment put on the market and the amount of WEEE that is processed.

3.6.1 The Transposition of the WEEE Directive in the UK

The WEEE directive required that all member states have nationally implementing legislation in place *by* 13 August 2004. However, in the UK (as in the most other EU states) the implementation of these legislative requirements was delayed. The Waste Electrical and Electronic Equipment Regulations 2006 (UK Government 2006) as amended by the Waste Electrical and Electronic Equipment (Amendment) Regulations 2007 (UK Government 2007) finally implemented the majority of the provisions of the European WEEE directive in the UK from 1 July 2007. These regulations establish the

foundations of the UK system for the separate collection, reuse, treatment, recovery and recycling of WEEE.

Under the WEEE directive, member states are free to determine the precise structure of the WEEE collection schemes. Belgium, Netherlands, and Sweden, which all had collection schemes in place prior to the WEEE directive, have a single national collection scheme. These schemes are run by not-for-profit companies established by the relevant trade associations. More details about these schemes is given in the next section.

The UK has opted for the "competitive clearing house model" which has been favoured by 16 of the 25 member states. The current UK system based on this model works on the principle of collective producer responsibility allowing producers to join compliance schemes to dispose their recovery and recycling obligations. Based on this approach, the UK government has considerably reduced its administrative burden by placing the reporting, financing and treatment compliance obligations on the operators of the producer compliance schemes, rather than directly on each individual producer. However, it should be noted that the WEEE regulations are still administered and enforced by the Environment Agency (EA) in England and Wales, the Scottish Environmental Protection Agency in Scotland and the Department of the Environment in Northern Ireland. The UK regulator is to recover its operational costs via registration fees on producer compliance schemes, producers, and waste exporters.

Under the UK's WEEE Regulations, every producer must be a member of a producer compliance scheme. Producers must provide the operator of the compliance scheme with details of the quantity and tonnage of all equipment put on the market for each of the ten categories of WEEE. These compliance schemes will be established by the private sector. The operator of each compliance scheme must register its members with the national regulator and provide it with details of all equipment put on the market by scheme members. The national regulator will determine the WEEE quota for each producer compliance scheme.

The scheme operator is responsible for financing the costs of compliance of the WEEE quota allocated to it by the national regulator for which its members are responsible. In

practice of course, the compliance scheme operator will pass those costs to its members. The scheme operator must ensure that the WEEE for which it is responsible is treated using the Best Available Treatment, Recovery and Recycling Techniques (BATRRT) either in the UK at an authorised treatment facility or overseas via an authorised exporter. The scheme operators must file compliance reports with the national regulator and these must be supported by evidence notes issued by the relevant authorised treatment facility or authorised exporter. Despite being obliged to be a member of a producer compliance scheme, a producer may choose to independently collect and treat WEEE from its own customers. Such producers are required to provide evidence of compliance to the operator of their compliance scheme.

3.6.2 Producer Responsibility Practices in other EU Member States

Before the entry into force of the WEEE directive, a number of producers organised the take-back and recycling of their waste products either on an individual basis or through collective recycling schemes. For example, IT producers started to establish individual electronics treatment and recycling processes in early nineties. These processes were primarily used for commercial asset management programmes which developed in response to:

- Increased customer pressure for asset management services and "environmentally responsible" disposal routes.
- The need for more control over second hand product markets.
- The need to prepare for producer responsibility legislation.

In addition, in the latter half of the nineties many European countries implemented national producer responsibility regulations or policies ahead of the WEEE Directive. In response, producers in these countries focussed on establishing "collective" recycling arrangements with their competitors. In those collective recycling schemes, the responsibility for organising treatment and recycling of WEEE discarded by consumers was shared amongst producers. The collective schemes used either subcontracted third parties to collect, treat, and recycle their products, or appointed one or more manufacturers to develop recycling facilities in-house.

In Switzerland, a collective scheme known as SWICO was established in 1994 for organising the treatment and recycling of IT goods (Mayers 2001). Although this was originally a voluntary scheme, producer responsibility legislation had been in place in Switzerland since 1998. The scheme sub-contracted twelve different recycling companies, each in a different region of Switzerland. Transportation from local collection points and retailers was organised by a single transportation company. SWICO financed the costs of logistics, treatment, and recycling operations by charging producers fixed fees per product sold to the Swiss market.

In the Netherlands, two collective systems were operating in parallel in 1999, serving both consumer electronics and white goods producers (known as NVMP) and IT producers (known as ICT) to meet requirements of producer responsibility legislation introduced in 1998 (Mayers 2001). These schemes both sub-contracted treatment and recycling responsibilities to Dutch recycling companies. Transportation and sorting of WEEE from municipal collection sites and retailers was organised by a collective consortium of waste management and logistics companies known as NVRD. NVMP financed recycling operations by means of a fixed visible fee charged to consumers at the point of product sale. Similar schemes to NVMP were established in Norway (ELEKTRONIKRETUR) and Belgium (RECUPEL). In contrast to NVMP, ICT recovered its costs by charging producers for products returned bearing their own brand (plus a proportion of products with no brands or for which the original producer no longer existed).

In Sweden, a scheme known as EL-KRETSEN was established to help producers comply with Swedish take-back law introduced in 2000 (ACRR 2003). EL-KRETSEN financed the transportation and recycling of all categories of WEEE by charging producers in proportion to their market share for each product category. Recycling was carried out using four different third party recycling companies, with transportation arrangements made on the basis of week-by-week competitive quotations from various logistics companies.

3.7 The Effects of WEEE Directive on the Recovery Sector

The WEEE directive has been a catalyst for dramatic reform and investment within the UK's WEEE recovery sector. The UK WEEE regulations introduced a new system *from* 1 July 2007 in accordance with the requirements of the European WEEE directive (DTI 2007) to:

- Maximise the separate collection of WEEE from other forms of waste;
- Ensure this WEEE is treated appropriately to protect the environment;
- Re-use, recycle and recover WEEE to target levels, and beyond the metallic content, for environmental protection and to contribute to greater levels of sustainable development;
- Dispose of any residual WEEE in an environmentally sound manner.

Given the complexity and wide-ranging nature of the WEEE Directive there remains some uncertainty as to how many businesses will be affected, both directly and indirectly, by the requirements of the Directive. However, the range of business sectors likely to be affected includes local authorities, manufacturers, distributors, repairers dismantlers, treatment facilities, secondary metal merchants and shredding facilities.

The majority of commercial end-users and manufacturers do not consider the operations involved in end-of-life treatment as their core business, and therefore outsource the end-of-life management of their products. In the UK, many electrical and electronic equipment manufacturers have followed this trend and have opted to conform to the WEEE directive by moving away from actively fulfilling the requirements themselves, in favour of utilising Producer Compliance Schemes (PCS).

There are at present 37 producer compliance schemes within the UK. A total of 4065 electrical and electronic producers have been reported to have registered with the UK regulator by PCSs (BERR 2007). Distributors are required to choose between in-store take back and participating in a Distributor Takeback Scheme (DTS). A vast majority of UK distributors (more than 75%) have joined the DTSs. The DTS membership fees have been made available to local authorities to support the upgrade and use of civic amenity sites as Designated Collection Facilities (DCFs). There are also a total of 1556 DCFs in

the UK, made up of local authority civic amenity sites, waste transfer stations, retail distribution centres, not for profit organisations and commercial organisation, to separately collect household WEEE (BERR 2007). These collection facilities collect the WEEE under five categories namely, large household appliances, cooling appliances, display equipment containing CRT, gas discharge lamps and all other WEEE. The compliance schemes are required to provide evidence of discharging their members' obligations and to finance the collection of WEEE from DCFs, treatment, reprocessing and recovery of used product at Approved Authorised Treatment Facilities (AATF) in accordance with WEEE treatment regulations in the UK. Figure 3.5 shows the main actors in the emerging WEEE recovery chain in the UK.

It is clear that the WEEE directive is impacting the existing recycling facilities mainly in two ways. Firstly, it puts constraints on how they operate in terms of treatment and disposal of equipment to make them more environmental-friendly. Secondly, it is forcing them to develop and establish profit making opportunity from recycling of WEEE.

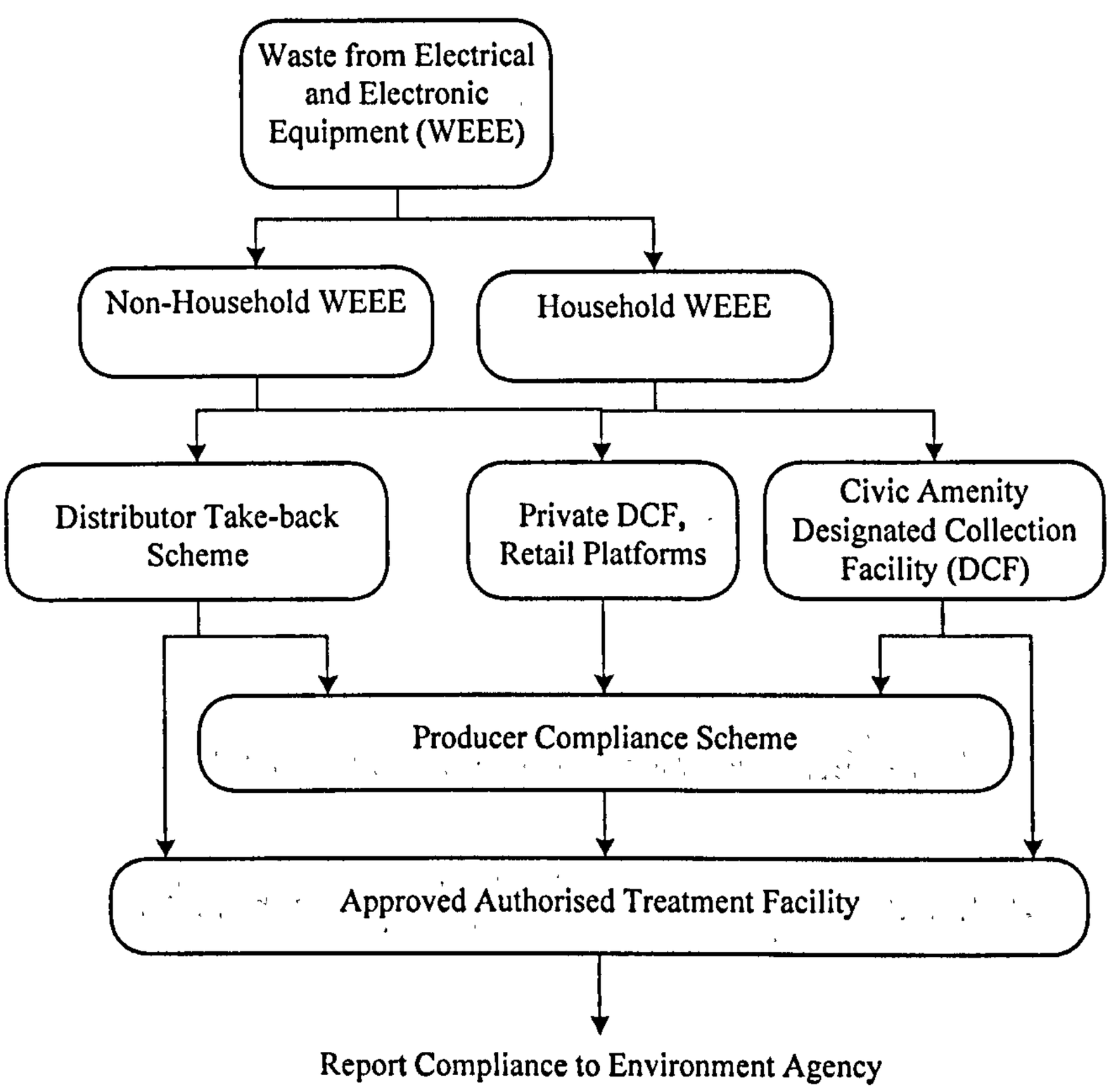


Figure 3.5: WEEE recovery chain in the UK

In the wake of such legislative pressures, the recycling facilities need to improve the value recovery from WEEE recycling to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable environmental and economical cost. This highlights the need for a systematic approach to aid decision making involved in the selection of the best possible end-of-life strategy for WEEE.

3.8 Current Shortcomings in WEEE Recovery and Recycling

The review of end-of-life activities within different recovery and recycling facilities has highlighted that current issues of WEEE recycling relate to recovery practices driven by economical reasons and lack of interest shown by manufacturers to take active involvement in the end-of-life management of their products. This has resulted in the inconsistencies and inefficiencies in the recovery and recycling of WEEE. In the UK, WEEE recycling is still in its infancy. At present, a subset of generated WEEE is collected and sent to recycling facilities in the UK. A report by Industry Council for Electronic Equipment Recycling (ICER 2000) found that with the exception of large household appliances typical recycling rates of WEEE in the UK are very poor (for example IT 26%, Telecom 50% and Video/sound 4%). Lack of product information to recyclers has been identified as a major issue hindering the effective end-of-life management of such waste. The following are some of the current shortcomings in WEEE recovery and recycling identified by this research.

- ***Recovery practices driven by economical factors:*** Historically the metal dominated products (white goods) have been targeted for recycling, to recover the ferrous metals. Such recycling activities have primarily been undertaken for commercial reasons to obtain the value from secondary metals without any consideration to the environmental impact of substantial quantities of waste being sent to landfill sites as shredder residues without any treatment.

- ***Lack of product data to facilitate recycling:*** Product structure and material composition information is a prerequisite for making an informed decision about selecting a recycling strategy for a particular product. However, currently in most cases access to this product data is not available to recyclers, resulting in inconsistencies and inefficiencies in recovery treatment of WEEE.

- ***Lack of manual disassembly to recover reusable parts and materials:*** The manual disassembly of parts and materials has never been attempted by the majority of recovery facilities mainly due to the lack of awareness among recyclers about the potential value of reuse through repair and remanufacturing. Although, for the vast majority of WEEE the opportunities for environmentally justified reuse and remanufacture are very limited due to technological obsolescence and high manual dismantling cost, such end-of-life options could still provide better solution than material recycling route.

- ***Contaminations in post-shredder material streams:*** The value of many post-shredder material streams depends on the material purity. Inefficiencies in the current shredding and separation processes are responsible for the contaminations in post-shredder material streams. One example is copper polluting the scrap steel, which alters the properties of the melted steel. This has such a negative impact on the value of scrap steel that some of the shredding operators in the UK employ hand-pickers to remove copper wires from scrap steel (Edwards *et al.* 2006).

- ***Inefficiencies in current applications of WEEE recovery:*** Currently there is little consistency regarding WEEE recycling due to lack of formal procedures to determine the best course of action for individual products. The complexity of materials contained within each product and the huge variety of products in electrical and electronic equipment, make existing applications of WEEE recycling highly ineffective in terms of both ecological and economical considerations.

3.9 Chapter Summary

This chapter has provided an overview of the current factors affecting WEEE recovery and the efforts made, both through legislation and by WEEE recovery chain to improve it. The review of regulations surrounding the recovery industry provided a valuable background to the increasing restrictions on waste management. The overview of the WEEE recovery chain highlighted that the legislative requirements for additional processing measures, such as depollution and the removal of hazardous substances have

reduced the profitability of the sector. Therefore, it is vital for the WEEE recovery industry to begin to understand the environmental and economical impacts of its recovery operations, so that the future WEEE salvage is based on environmentally sustainable strategies that are also economically feasible.

The existing and future concerns in terms of legislative compliance and the increasingly competitive business environment for different stakeholders in recovery chain for WEEE highlight the need for a systematic recycling approach. The particular approach should address the shortcomings in the current recovery and recycling to effectively maximise the recyclability of WEEE and minimise the environmental and economical impact of its recycling and disposal. To reduce the environmental impact of end-of-life electrical and electronic equipment and increase the economic benefits of its recycling, a recycling process planning framework would be described in chapter 7 to provide a holistic assessment to facilitate WEEE recycling.

Chapter 4

An Overview of Research Related to WEEE Recycling

4.1 Introduction

This chapter reviews prior academic research and literature related to the scope of the research included in this thesis. The initial part of the chapter describes a background of evolving environmental concerns and the emergence of environmentally conscious manufacturing concept. The main part of the chapter provides a detailed review of various research areas around WEEE recovery and recycling. Finally, the prior research work on the end-of-life management of WEEE is critically analysed.

4.2 Environmentally Conscious Manufacturing

Our planet has finite resources and their wasteful use has been creating concerns among different stakeholders. All industrial activities are consuming earth's natural resources such as raw materials, fossil fuels, energy, land, water and air. A number of ecological problems such as global warming, ozone depletion, acid rain, and natural resource scarcity are thought to be due to industrial activities. There have been various responses from a number of different parties to combat these environmental problems. The concept of sustainable development was introduced by the World Commission on Environment and Development in 1987 (Brundtland 1987). The Montreal Protocol (UNEP 1987) on substances that deplete the ozone layer is a landmark international agreement designed to protect the stratospheric ozone layer. In 1992, Earth Summit saw the largest number of world leaders' participation in Rio de Janeiro. The theme of this meeting was to make critical decisions about how the world economies should be run to secure the future of the planet. In response to the growing amount of COx emissions and global warming, Kyoto Protocol was introduced in 1997 which assigns targets to reduce the emission of greenhouse gases to industrialised countries.

The concept of sustainable development has its implications in the manufacturing industry, i.e. the reduction of wasteful consumption of natural resources and the

prevention of pollution during entire life-cycle of products. In addition to these international initiatives and legislation to promote sustainability in production activities, there is an increasing demand by customers (Vandermerwe and Oliff 1990; Weissman and Sekutowski 1991), suppliers and the general public (Frosch 1994; Jennings and Zandbergen 1995) from manufacturing firms to minimise any negative impact of their products and operations on the environment. Consequently, the research in this area has led to the emergence of a new concept referred to as Environmentally Conscious Manufacturing (ECM) (Weissman and Sekutowski 1991; Watkins and Granoff 1992; Sarkis 1995). ECM is concerned with developing equipment, methods and procedures for manufacturing activities from concept design to final disposal (including reuse and recycling) such that the environmental standards and requirements are satisfied.

In literature, there are a number of review papers which take ECM approaches from different aspects. Gungor and Gupta (1999) present a comprehensive review about ECM and product recovery and cover all the areas of ECM. O'Shea *et al.* (1998) have reviewed state-of-the art literature on disassembly planning. Guide *et al.* (1999) and Bras and McIntosh (1999) present two overviews of research on remanufacturing planning and control. Mizuki *et al.* (1996) and Zhang *et al.* (1997) provide the state-of-the-art survey in the area of design for the environment.

The academic research undertaken within different areas included in ECM which are related to the scope of research reported in this thesis is described in the subsequent sections of this chapter.

4.3 Life Cycle Analysis

Life Cycle Analysis (LCA) is a process for assessing and evaluating the environmental, occupational health and resource consequences of a product through all phases of its life, i.e. extracting and processing raw materials, production, transportation and distribution, use, remanufacturing, recycling, and final disposal (Alting 1993; Alting and Jorgensen 1993). A LCA study facilitates the systematic collection, analysis and presentation of environmentally related data. There are four main steps involved in LCA as outlined below (Miettinen and Hämäläinen 1997; Gungor and Gupta 1999).

- **Goal and Scope Definition:** This stage defines the boundaries of the system being assessed.
- **Inventory Analysis:** This stage determines the flow of material and energy through the defined system.
- **Impact Assessment:** This stage uses the data collected by the inventory analysis and classifies it into impact categories defined by the scope.
- **Interpretation:** Results from the LCA are verified and tested, and conclusions are reported.

There are a large number of corresponding publications, which demonstrate LCA in example case studies in order to identify common practises (Alting and Legarth 1995; Kalisvaart and van der Horst 1995; Harsch *et al.* 1996). Brodersen *et al.* (1994) presents an analysis of the various chemicals present throughout a completely destroyed printed circuit board. DeRon and Penev (1995) note that the motivation for electronic disassembly that is spurred by the recovery of precious metals may soon fade as electronic products are expected to contain less precious metals.

LCA is a complex analysis and therefore, there is a requirement for utilising the power of computers for collection, organisation, and analysis of the relevant data to cope with this complexity. There have been a number of computer based LCA software tools, developed by Ishii *et al.* (1994), Rosen *et al.* (1996), Hooks *et al.* (1997) and are classified by Sweatman and Simon (1996). In addition a number of researchers have focused on the use of knowledge-based techniques for life cycle design (Biswas *et al.* 1995; Hattori *et al.* 1995; Watkins *et al.* 1995; Kleban *et al.* 1996).

However, much of the information required for an accurate LCA study is either unavailable or unreliable, and some of the steps require subjective judgements. Attempts have been made to simplify LCA into a single indicator to effectively highlight environmental impacts, such as Vogtlander *et al.* (2002) and Eco-indicator methodology (PRE Consultants 2000).

4.4 Design for Environment

Design for Environment (DfE) is a design paradigm, which comprises of techniques and methods to design products so that they have minimal negative impact on the environment. The idea is to incorporate the knowledge gained through LCA into the design in order to create environmentally friendly products using environmentally friendly processes. This design philosophy is in contrast to past design approaches that sought planned obsolescence of products, functional redundancy, and over-design for aesthetic and product differentiation (Shrivastava 1995).

According to Fiksel (1996), DfE can be broken down into various stages such as consideration for manufacturing, consumer use and end-of-life of the product. At each of these stages, different forms of design strategies can be utilised. For example at the manufacturing stage, the design objective could be to design products and processes, which need minimum energy and material consumption for production. Similarly the environmental issues during the usage stage, such as savings on energy consumption, long life, serviceability etc. can be incorporated into the design decisions. The ultimate goal of DfE is to minimise the overall environmentally damage when producing goods and services. Availability of guidelines, checklists and software based DfE tools also aid the designer to achieve this goal (Glantschnig 1994). Among these several systems have been diagnosis and decision-making tools that are derived from qualitative environmental data (Mizuki *et al.* 1996). The use of quantitative data such as the Analytical Hierarchy Process, Discounted Cash Flow has been also reported by Veroutis and Fava (1996) and Azzone and Noci (1996).

Rivera-Becerra and Lin (1999) criticised these earlier efforts for relying on personal evaluation in decision-making and developed a methodology to quantify the degree of environmental consciousness of a product with the aim of enhancing decision-making at the design stage through the application of statistical methods and fuzzy set theory. Feldmann *et al.* (2000) examined academic research in the area of environmentally conscious design and attempted to identify the extent to which this research supports industrial practices. Some of the other research efforts to support DfE include the development of tools for the selection of materials (Wegst and Ashby 1998) and selection of appropriate end-of-life strategies (Rose and Stevels 2001).

4.4.1 *Design for Disassembly*

Design for Disassembly (DfD) gives particular significance to improving the ease of parts separation. Mok *et al.* (1997) states that concepts which attempt to improve dismantling should include disassembly without force, no repetition of same or similar materials, easy recognition of disassembly points, design of simple product structures, and prohibition of toxic materials. Kroll and Carver (1999) highlighted four sources of disassembly operation complexity, which were accessibility by hand or tool, the positioning precision required by the hand or tool, the force required, and the base time required to complete the task. The initial development of DfD techniques drew similarity with the Design for Assembly (DfA) techniques introduced by Boothroyd *et al.* (2002), and were based on the assumption that the sequence of assembly is reverse of disassembly. However, Kroll and Carver (1999) state that although they are similar in intent, many DfA based products are not easy to disassemble. An example is given of a snap fit joint that requires little effort to close, but is nearly impossible to open due to a lack of tool clearance. Hundal (1994) states the DfD lead to modular type of design that promote the replacement and recycling of modules rather than the complete product destruction.

4.4.2 *Design for Recycling*

Many different techniques exist to improve the end-of-life characteristics of a product during its design. Design for Recycling (DfR), which aims to increase end-of-life recycling through improved material selection, is a central element to DfE, with Gungor and Gupta (1999) describing its general characteristics as:

- Long product life with the minimised use of raw materials (source reduction),
- Easy separation of different materials,
- Fewer number of different materials in a single product while maintaining compatibility with the existing manufacturing infrastructure,
- Fewer components within a given material in an engineered system,
- Increased awareness of life cycle balances and reprocessing expenses,
- Increased number of parts or subsystems those are easily disassembled and reused without refurbishing,

- More adaptable materials for multiple product applications and
- Fewer 'secondary operations' reducing the amount of scrap and simplifying the recovery process.

Henshaw (1994) classified the manufacturing conditions in which the implementation of DfR is most sensible:

i. When the required materials are rare or potentially difficult to obtain;
ii. When the required materials are hazardous;
iii. When there is an economic incentive for material recovery;
iv. When there is an obvious benefit to the environment; and
v. When recycling or product disposal is legislated.

Some interesting issues that arise from this list include the determination of an "obvious benefit to the environment" and the level of potential harm to a company's public perception when product disposal is legislated and recovery is not an alternative. At first, the recycling process appears to be always beneficial to the environment. In fact, the process should be completely evaluated, taking into account the energy expenditure and pollution costs that are required in obtaining the product, disassembly, reprocessing, remanufacturing, quality testing, and marketing and sale. Proper disassembly and recycling of electrical and electronic products requires obtaining specific information about the product, and projecting the remaining life and reliability of its components

4.5 Waste Management

Waste management is defined as "the collection, transport, recovery and disposal of waste, including the supervision of such operations and after-care of disposal sites" (The European Commission 2006). Waste generation in the European Union is estimated at about 1.3 billion tonnes per year; including waste from manufacturing (338 million tonnes), from mining and quarrying (377 million tonnes), from the construction sector (286 million tonnes), municipal solid waste (182 million tonnes) and hazardous waste (27 million tonnes) (The European Commission 2003a). Furthermore, significant amounts of wastes are also produced by agriculture, forestry, fishery, and service and public sectors. In general, waste generation in the EU is increasing at rates comparable

to economic growth. This rapid increase in waste generation is expected to continue, in particular generation of post consumer waste. In addition, in most countries landfilling is still the most common practice of waste treatment. In order to combat the problems that could stem from landfilling the post consumer waste, the European Commission has issued the Directive on Waste (2006) which prohibits the landfilling of wastes.

4.5.1 The Waste Management Hierarchy Concept

The waste management hierarchy is broadly accepted as the guiding principle for securing a more sustainable waste management system (The European Commission 1975). The hierarchy sets out the order in which the waste management should be considered based on the environmental impact, as depicted in Figure 4.1.

Following this hierarchy, prevention of the waste is the top priority of waste management solution. Reduction of waste, which is also referred as waste minimisation, aims to reduce or generate less waste, in the first place, through efficient use of materials, better design and reduced operational costs (Monkhouse and Farmer 2003). Dematerialisation and a move towards services instead of products referred to as 'Product-Service System' (PSS) offer potential for significant sustainability benefit (Evans *et al.* 2007).

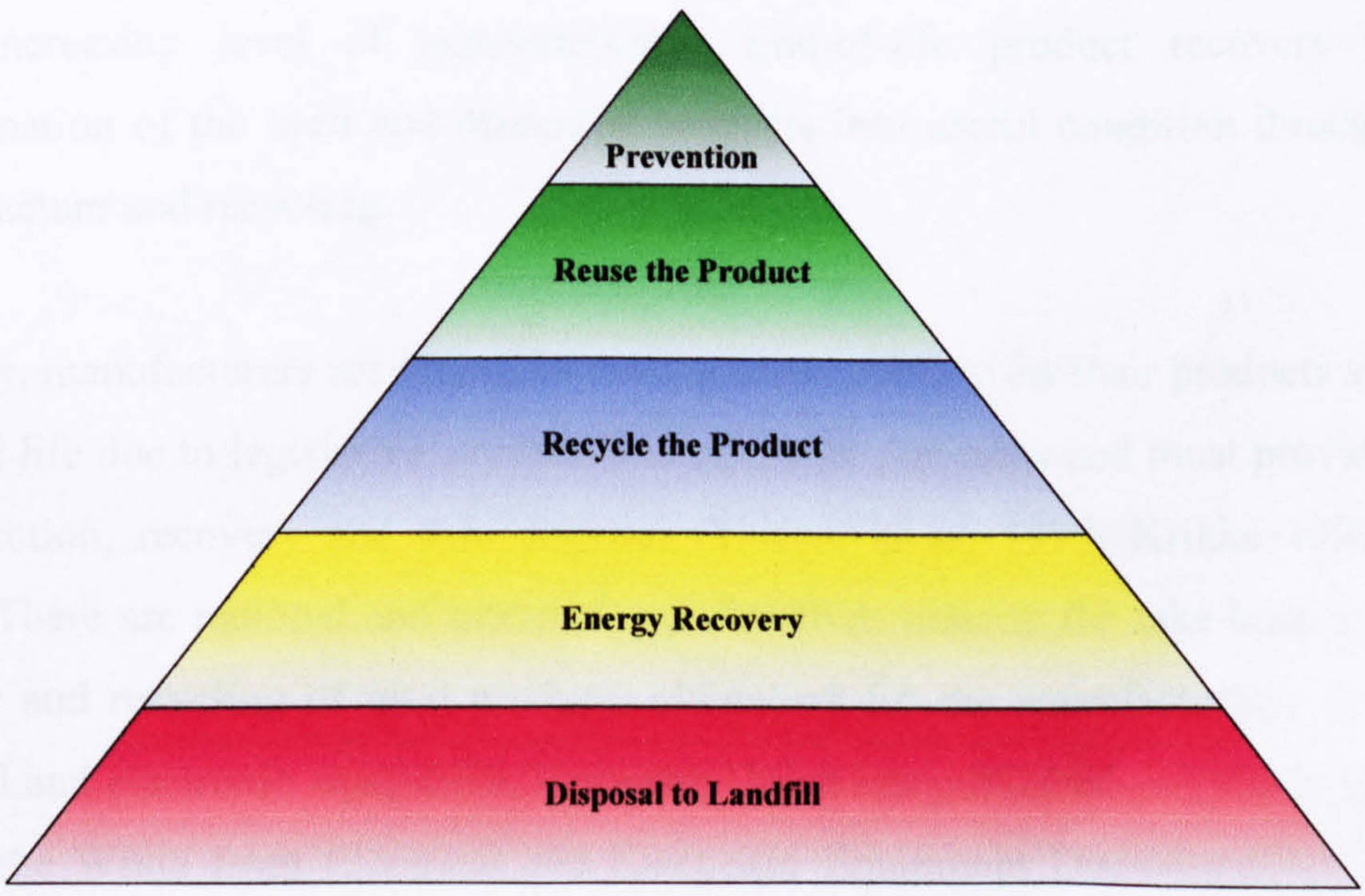


Figure 4.1: The waste management hierarchy

The second preferred option is to reuse the products with minimal requirement for further processing. Reuse includes any operation by which products and components are used for the same purpose they were conceived in the first place. Recycling of the product for material recovery is the third preferred option. Energy recovery or incineration of waste comes after the product recycling for material recovery. Finally, disposal of the product in landfill is considered as the worst waste management option. However, it should be mentioned that the waste hierarchy concept has its own limitations. It is too simplistic to be applied in real life situations and does not incorporate the sustainability dimensions for reaching judgements about the preferred option within the waste hierarchy. It should, therefore, only be regarded as a general guideline to determine waste management options. In order to determine the best waste management option for a particular product, a detailed assessment considering different aspects of sustainability is needed.

4.6 End-of-Life Product Recovery

When a product reaches the end of its functional life, it can be recovered in a variety of ways. Understanding and developing methods for the end-of-life management of products by means of material and product recovery are extremely crucial considering the amount of post consumer waste generated. In a world of limited resources and disposal capacities, EoL product recovery is the key in supporting a growing population at an increasing level of consumption. End-of-life product recovery involves transformation of the used and discarded products into useful condition through reuse, remanufacture and recycling.

Currently, manufacturers are facing increasing responsibility for their products at the end of useful life due to legislative, societal and customer pressures and must provide means for collection, recovery and safe disposal (Thierry *et al.* 1995; Krikke 1998; Guide 2000). There are national and international directives making the take-back and reuse, recovery and recycling of used products obligatory for the manufacturers. In case of electrical and electronic equipment, European Union has published two major directives, namely the Waste from Electrical and Electronic Equipment Directive (The European Commission 2003c) and the Restriction of certain Hazardous Substances in Electrical and Electronic Equipment Directive (The European Commission 2003b) as outlined in

chapter 3. Although, the main motivations for end-of-life product recovery are complying with legislation and green image, in some cases it is also pursued due to hidden economic value of used products. Various research areas related to EoL product recovery are presented in the following sections. It should be mentioned that EoL product recovery has been approached from a wide array of disciplines in the literature including operations management, engineering, economics, marketing and logistics etc. However based on the scope of the research in this thesis, the review presented in the next sections is focusing on operations management literature on EoL product recovery.

4.6.1 End-of-Life Product Recovery Options

End-of-life product recovery can be achieved in different ways, which are known as end-of-life product recovery options. An end-of-life option is the approach or strategy associated with dealing with the recovery of product at the end-of-life. Rose (2000) define end-of-life as the point in time when the product no longer satisfies the initial purchaser or first user. In the literature, various taxonomies offer alternative perspectives to distinguish among end-of-life product recovery options. In general, two forms of recovery for the used product are commonly recognised, namely remanufacturing and recycling. According to Fleischmann *et al.* (1997) remanufacturing is recovering the product as a whole through a series of operations, which may include disassembly, replacing or repairing bad components, reconditioning, and reassembling. Goggin and Browne (2000b) further distinguish component recovery referring to reclamation of parts and modules from the used products. Based on work in Rose (2000), Table 4.1 defines the different product recovery end-of-life options.

Remanufacturing differs from repair operations, in the sense that products are disassembled completely and all parts are returned to like-new condition. Lund (1998) has developed the following list of criteria for a discarded product to be eligible for remanufacturing.

- The product is a durable good
- The product fails functionality
- The product is standardised and the parts are interchangeable
- The remaining value-added is high

End-of-Life Option	Definition
Product Reuse	Reuse is the second hand trading of product for use as originally designed.
Remanufacture	Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled. Parts from a specific product are not kept with the product but instead they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled on an assembly line using those recovered parts and new parts where necessary.
Recycling with disassembly	Recycling reclaims material streams useful for application in products. Disassembly into material fractions increases the value of the materials recycled by removing material contaminants, hazardous materials, or high value components. The components are separated mostly by manual disassembly methods.
Recycling without disassembly	The purpose of shredding is to reduce material size to facilitate sorting. The shredded material is separated using methods based on magnetic, density or other properties of the materials.
Disposal	This end-of-life option is to landfill or incinerate the product with or without energy recovery.

Table 4.1: Definitions of end-of-life options (Rose 2000)

- The cost to obtain the failed product is lower than the remaining value-added
- The product technology is stable
- The consumer is aware that remanufactured products are available

On the other hand, recycling is recovering the material content of the product via specialised processes at the end of which the identity of the product is lost. In general, after removing the reusable components, the material separation is performed by various techniques depending on the material characteristics. Then recycling processes are performed on the different types of material (Owen 1993). The relationships between the end-of-life product recovery options are summarised by Thierry *et al.* (1995) as shown in Figure 4.2.

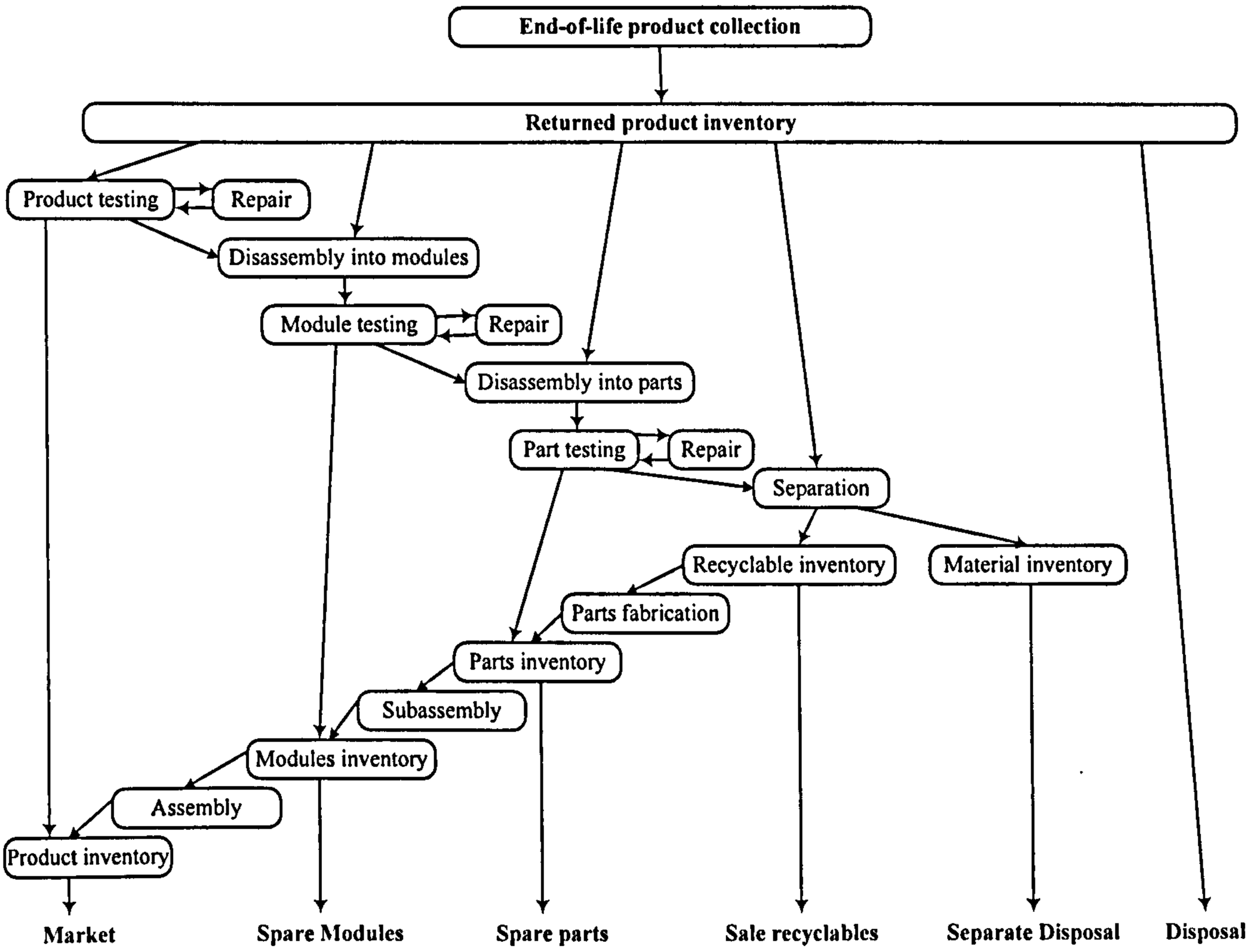


Figure 4.2: The product recovery activities (Thierry *et al.* 1995)

4.6.2 Operational Issues in Product Recovery Environments

The product recovery environment compasses organisations, which are involved in end-of-life recovery of the used and discarded products. A product recovery environment may comprise a manufacturing company, which incorporates product take-back and integrates production and recovery lines. Alternatively, it may comprise of an independent product recovery company, either anonymously or on a subcontract basis, which collects the used products, re-process them and sells the recovered products (Rahimifard 2004). A summary of the scope of activities within product recovery environments is given in Figure 4.3. Operational characteristics of the activities within product recovery environments are different than the traditional manufacturing activities. Generally, a high level of uncertainty regarding the timing, quality, quantity of returned products necessitates high level of flexibility and agility. In the following subsections, the operational management issues and related tools in product recovery environments will be overviewed and the relevant research presented.

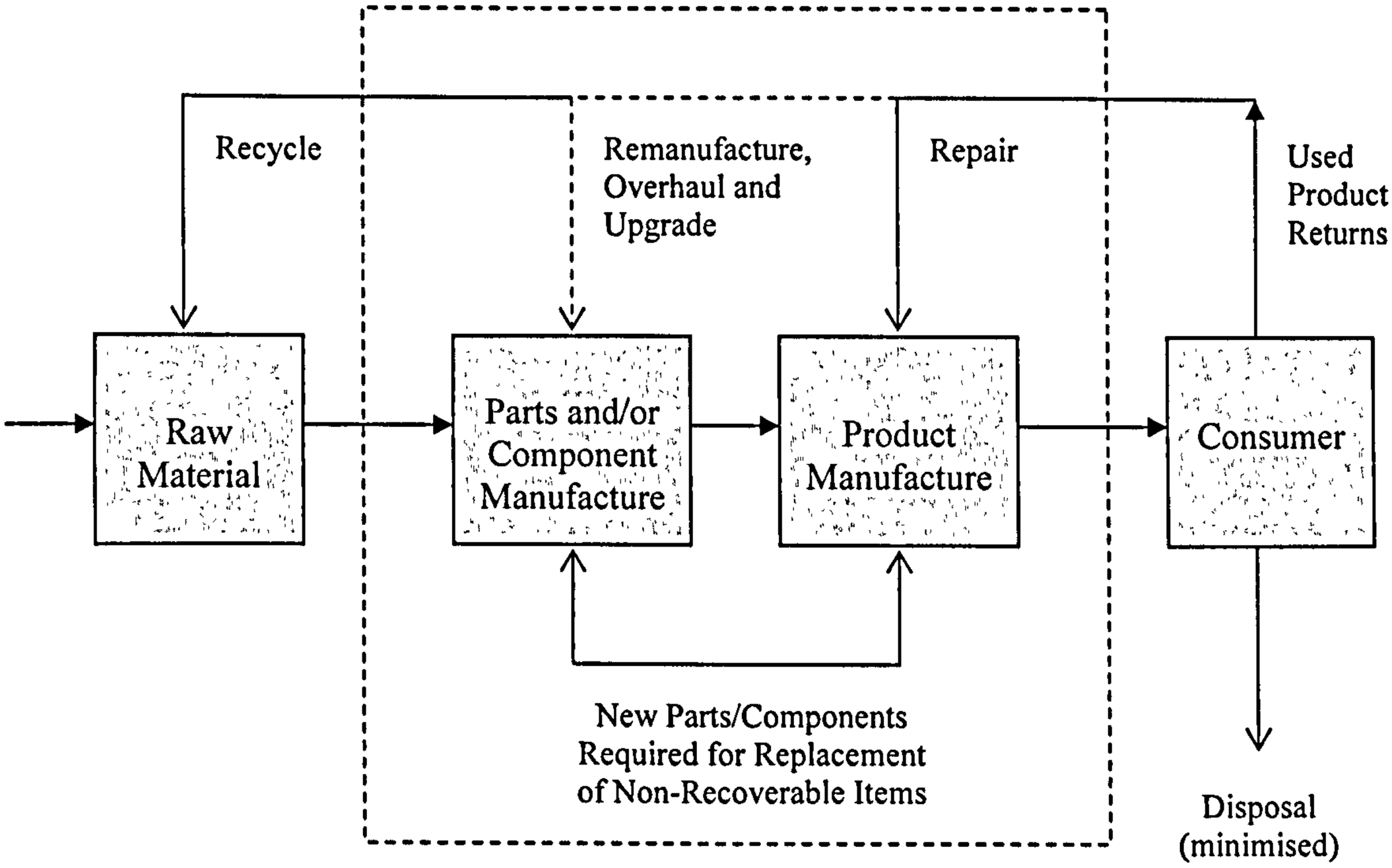


Figure 4.3: Range of activities within product recovery environments (Guide *et al.* 1999)

4.6.2.1 Disassembly

Gupta and Taleb (1994) define disassembly as a systematic method for separating a product into its constituent parts, components, subassemblies, or other groupings. Since it is a part of almost all recovery options and widely affects operations planning, issues related to disassembly receives considerable attention by researchers. Disassembly is not simply the reversal of assembly process and has different operational characteristics. Although the actual mechanism of disassembly is simpler than that of assembly, the operational scope of disassembly is much more complex (Tani and Guner 1997). Brennan *et al.* (1994) compares the general operational characteristics of assembly and disassembly systems. Table 4.2 presents the results of this comparison. Although there are similarities between these two systems, they report many differences such as single versus multiple demand sources, single end item versus multiple end items, different planning horizons and by product inventory items. Uncertainty regarding the quantity and quality of the disassembly outcomes is also recognised as a complicating factor for operations planning within disassembly systems.

System Characteristics	Assembly	Disassembly
Demand	dependent	*dependent*
Demand sources	single	*multiple*
Forecasting requirements	single end item	*multiple item*
Planning horizon	product life-cycle	*indefinite*
Design orientation	design for assembly	*design for disassembly*
Facilities and capacity planning	straightforward	*intricate*
Manufacturing system	dynamic	*dynamic*
Operations complexity	moderate	*high*
Flow process	convergent	*divergent*
Direction of material flow	forward	*reverse*
Inventory by-products	none	*potentially numerous*
Availability of scheduling tools	numerous	*none*

Table 4.2: Comparison of assembly and disassembly systems (Brennan *et al.* 1994)

Gungor and Gupta (1999) divide disassembly research into two main groups: namely disassembly levelling and disassembly process planning. Disassembly levelling is related to identifying the extent to which disassembly of the product should be performed to keep the profitability and environmental features of the process at a desired level. It is important to find a balance between the cost of disassembly and the returned benefit from it. In the literature, this analysis has been carried out usually by cost analysis using various techniques (Navin-Chandra 1994; de Ron and Penev 1995; Lambert 1997).

Disassembly process planning is finding a sequence of disassembly tasks to minimise the cost of disassembly. A disassembly process plan is a sequence of disassembly tasks which begins with a product to be disassembled and terminates in a state where all of the parts of interest are disconnected (Gungor and Gupta 1999). The number of alternative disassembly process plans grows exponentially as the number of the components increase in a product. Researchers have used various methods and developed tools to optimise the disassembly sequence including genetic algorithm (Seo *et al.* 2001), graph-based heuristics (Lambert 1997), neural networks and Petri nets (Gungor and Gupta

1999). A more detailed view on disassembly planning can be found in Gupta and McLean (1996), O'Shea *et al.* (1998) and Wiendahl *et al.* (1999).

4.6.2.2 Inventory Planning, Production Planning and Reverse Logistics

Inventory planning and control comprises of all activities and procedures used to control and maintain the stock levels to support production at minimum cost. For the traditional manufacturing environment there are an abundance of well established methods and tools to achieve effective inventory planning and control. However, inclusion of product recovery changes the operational scope of inventory planning and control. In this context, an inventory control model is required to keep track of returned products, partially disassembled products, disassembled parts as well as new parts. In addition to this multiplicity of the inventory items, there are further complications due to a high degree of uncertainty in timing, quantity and quality of returned products and demand for recovered parts. This makes inventory control within product recovery environment a very complex task.

In the literature, classic inventory control techniques such as reorder point and economic order quantity have been modified accordingly and applied in product recovery environments. These applications can be grouped as deterministic and stochastic models for product recovery systems. Deterministic models in which the return and demand rates are known in advance, have been developed by some modifications to the classical Economic Order Quantity formula (Mabini *et al.* 1992; Richter 1997). However, stochastic models provide better control for the uncertainty inherent in the nature of product recovery systems. These models include periodic review models and continuous review models (Muckstadt and Isaac 1979; Kelle and Silver 1989; Inderfurth 1997).

The role of production planning and control in recovery environments includes determining how much and when to disassemble, to remanufacture, and to recycle, how much to produce and/or order for new material and coordinate disassembly and reassembly. Figure 4.3 presents an overview of production planning and control activities within product recovery environments.

There has been many research works on application of traditional production planning and control methods in product recovery environments. Some researchers investigate application of material requirement planning with some modifications in recovery environments (Panisset 1988; Flapper 1994; Gupta and Taleb 1994; Thierry *et al.* 1995). They formulate a reverse bill of material. However, the deterministic nature of material requirement planning does not make it appropriate for the product recovery environments, since high uncertainty is one of the major characteristics for such applications (Fleischmann *et al.* 1997).

Products or parts destined for remanufacturing, recycling or disposal create a new material flow from user to the reprocessing environments, which is the opposite direction of the conventional production supply chain. The logistic system that is designed to manage this flow is commonly referred to as 'reverse logistics' (Fleischmann *et al.* 1997; Dowlatshahi 2000). The main issues in reverse logistics are decisions regarding collection and transportation, the number and location of take-back centres, incentives for product returns, and third party service providers (Guide 2000). Goggin *et al.* (2000) define a reverse logistic network as the "product recovery chain", which includes collection, assessing, routing, recovery, and distribution.

4.7 End-of-life Management of WEEE

The production of electrical and electronic equipment is rapidly increasing due to technological innovation, market expansion, shorter product life cycles and improvements in economy (The European Commission 2000b). Parallel to this development, environmental degradation has become a big concern and governments around the world are formulating "producer responsibility" laws to put pressure on companies to manufacture products having minimum eco-burden (Boks 2002; Jofre and Morioka 2005). The consumption of scarce materials in the manufacture of electrical and electronic equipment and its disposal to scarce landfill sites along with environmental problems caused by electrical and electronic waste has caused concerns among the governments, environmentalists, manufacturers and consumers. This has prompted many manufacturing firms to become environmentally responsible and embrace the end-of-life management in their business models.

Generally, the end-of-life management involves product take back, pre-treatment and processing of the end-of-life product for effective recovery and recycling. There has been a wide array of research activities related to the end-of-life management of WEEE. Some of the most notable ones among these include design for end-of-life, disassembly, automated disassembly, end-of-life costing, optimal part disposal models, eco-efficiency, disassembly bill of material, embedded information devices, and bulk recycling and are outlined below.

For identifying the ways in which product characteristics influence how WEEE is processed at the end-of-life, valuable insight can be obtained by researched design tools. Kang *et al.* (2001) propose an Assessment Tool for Recycling Oriented Design (ATROiD), which is a design support tool for end-of-life considerations. It groups several parts together into so called 'recycling segment' which results in cost minimisation associated with end-of-life. ATROiD calculates the disassembly time, end-of-life cost and recycling potential, and suggest improvement options. Das and Yedlarajiah (2002) present an optimal part disposal model, which sets out to solve the problems faced by disassembly facilities in identifying how and at what level to dismantle WEEE and then sort the disassembled fractions according to pre-determined material or part streams. The model is formulated as a mixed integer programme that attempts to maximise the net profit in product recycling by considering expected revenues from the sale of reusable parts and materials streams. They note that there is a lack of information about the valuable content in discarded products which is a reason why WEEE is not often evaluated for product disassembly.

As for the technological developments that could have an impact on the way the WEEE is processed in the future, a research stream focussed on automated disassembly and active disassembly. Knoth *et al.* (2001) note that automated disassembly concepts are very inflexible and usually focus special task or product, making this an un-economical approach. They suggest that future research should focus on making automated disassembly a more flexible option and to focus on developing modular systems for the flexible disassembly cells for disassembling families of similar products. Automated disassembly, if successfully implemented, has the potential to reduce the high labour costs involved in manual disassembly. Similarly, the research in the field of active disassembly has focussed on the replacement of the conventional fasteners by joining

elements made of 'smart' materials providing a shape memory effect (Chiodo *et al.* 2000). The idea behind active disassembly is that the exposure of the product to an increased ambient temperature triggers the shape recovery of the smart fastening devices resulting in the self-disassembly. A variety of materials with shape memory effects are explored for the potential use in electrical and electronic equipment.

A very common problem associated with the disassembly of WEEE is the lack of product information available to recyclers. This lack of product information precludes the reclamation and recycling of the end-of-life products. The information required for effective product recycling include computer aided design diagrams and bill of material, which manufacturers are always reluctant to provide. Given the current implementation of the WEEE directive in the UK, where majority of electrical and electronic equipment manufacturers have opted to join the collective compliance schemes to dispose their recovery and recycling obligations, it is highly unlikely that the manufacturers will make product design and materials information public. Das and Naik (2001) propose a Disassembly Bill of Material (DBOM) standard that contains much of the bill of material information necessary to facilitate the disassembly and subsequent product recycling. The proposed standard contains data tables for the parts and their joining relationships, and fastener data. Emerging technologies providing product information at the end-of-life include Radio Frequency Identification (RFID) (Parlikad and McFarlane 2007) and embedded information devices (Kiritsis *et al.* 2003). RFID allows remote interrogation of objects using radio waves to read data from RFID tags which are at some distance from an RFID reader. One of the major impacts reported of these new technologies is the improvement in the effectiveness of decisions made during end-of-life product recovery.

Although a number of methods and techniques have been developed to aid the ease and automation of disassembly process, in majority of cases disassembly of products still remain economically not viable. Recycling of products with little or no disassembly is referred to as bulk recycling. There are some studies in the literature, which investigate the ways of improving efficiency in bulk recycling of WEEE (Sodhi and Knight 1998; Ploog and Spengler 2002; Stuart and Christina 2003).

The environmental attributes of a product are largely determined during the design stage (Baumann *et al.* 2002). However, the environmental and economical impacts of a product during its life cycle also depend on its end-of-life management. This is especially true for electrical and electronic products where the EoL stage has a high environmental and economical impact. The EoL decision is recognised as a multi-objective decision and should be based on technical, financial, environmental and increasingly legislative constraints. A critical review of decision support tools for the end-of-life management of WEEE is presented in the next section.

4.7.1 Decision Support Tools for the End-of-Life Management of WEEE

The global increase in the production of electrical and electronic equipment is being met with an attempt to improve the end-of-life treatment of WEEE in order to avoid or reduce the amount of such waste disposed to landfills. Although legal pressure is being applied progressively to divert waste from landfill and to encourage reuse and recycling options, the current end-of-life management for the products included in WEEE continue to focus on economical issues alone. For recovery and recycling of WEEE, several decision factors should be considered which determine the maximum environmental benefits that can be achieved for a given economic cost while meeting the legislative compliance when a product reaches its EoL.

For a given end-of-life product, the selection among the options of product or part recovery, material recovery (recycling) or disposal is commonly referred to as the EoL decision, and it is closely related to disassembly levelling and planning as well as product recovery and recycling planning. There are number of research studies on developing decision support methods and tools in order to aid the selection of recovery options using linear programming, dynamic programming and data comparison analysis for various product types (Clegg *et al.* 1995; Johnson and Wang 1998; Krikke *et al.* 1998; Low *et al.* 1998). The main objective in theses approaches is to maintain the profitability and not to violate the technical feasibility constraints. However, these were rather isolated technical solutions without integration to other functions of operations planning. On the other hand, Goggin and Browne (2000a) have incorporated demand requirements and supply availabilities to EoL decision making. In their work, the choice among the predetermined recovery options is dependant on the inventory levels and

demand indicators received at the particular time. Erdos *et al.* (2001) and Bufardi *et al.* (2004) are among the first research works to extend the EoL selection criteria to include social and environmental factors. They developed a multi-criteria decision aid, which ranks the alternative recovery options using a predefined list of indicators.

Lichtenvort *et al.* (2001) present a cost management system for greening electrical and electronic equipment, known as grEEEn method, which provides manufacturers with a tool to assess their products on three main aspects, namely, legal compliance with WEEE and RoHS compliance, economic, and environmental impacts of various design solutions chosen. This method uses the process model and the product model for the required assessment. A similar design for end-of-life support model, known as 'product material recycling cost model' to calculate the costs or revenues of mechanically processing a product based on product's material composition was developed by Boks (2002). The model does not consider the dismantling processes prior to shredding.

Some studies have incorporated both cost estimation and environmental impact estimation for the decision support at the end-of-life. However, these studies mainly provide the assessment on macro level. For example, Rose *et al.* (1999) present a design oriented decision support framework which focuses on technical product design variables such as expected life time and number of parts to select an appropriate EoL strategy for a product at the design stage. Krikke *et al.* (1998) describe a method on a tactical management level to determine the best recovery and disposal strategy of product type considering technical, economical and ecological criteria. Yu *et al.* (2000) adopt analytical hierarchic process to find the best recycling strategy for products in WEEE in which environmental impact, cost and reclaimed materials were considered as the major criterion for strategy selection.

Lamvik *et al.* (2002) present 'an end-of-life of product systems' referred to as AEOLOS methodology to determine the most appropriate EoL option (reuse, material recycling, incineration or disposal) based on economic, environmental and societal criteria. The basis of the decision in this descriptive methodology is a defined product scenario consisting of different end-of-life options linked to a detailed product description model which is assessed based on various aspects of sustainability and compared with the

alternative scenarios. This is a high level tool to assist the user to select a relatively sustainable product end-of-life scenario but lack operational support required for EoL product recovery for complex WEEE stream.

Reimer *et al.* (2000) have proposed a recycling model for end-of-life electronic products to minimise the cost of different EoL activities like collection, disassembly, and material separation sequences by establishing separate models for each activity and using genetic algorithms. Huisman *et al.* (2003) describe 'the quotes for the environmentally weighted recyclability' or QWERTY approach which focuses on the determination of environmentally weighted recycling scores rather than weight-based recycling scores. QWERTY approach considers the environmental value of secondary materials and the environmental burden of EoL treatment itself. Although, QWERTY approach is quite powerful in assessing the effectiveness of end-of-life processing, the consequences of design of products with respect to recyclability issues and the consequences of the WEEE directive on the take-back and recycling of electrical and electronic equipment, it does not provide the operational support to identify the best end-of-life recovery and recycling processes for WEEE. Herrmann *et al.* (2002) describe a method to calculate economical and ecological indicators to evaluate electrical and electronic waste in regards to material recycling, and used life cycle assessment and life cycle costing to calculate these indicators. This assessment approach only focuses on the material recycling route of product recycling excluding the higher options on waste hierarchy e.g. reuse, remanufacture etc. and results into two indicators needing further interpretation to reach a final decision.

4.8 Chapter Summary

This chapter has provided an overview of the research activities in different areas related to the scope of this research. The increasing interest, as evident by a number of national and international legislations, on the concept of broadening manufacturer's responsibility is challenging the current product recovery environments. Although, there has been significant academic research which focuses on different areas of waste management and end-of-life product recovery, there is a lack of practical implementation of decision support for a systematic approach to product recovery procedures in electrical and electronic recovery sector.

Furthermore, as a result of the review undertaken in this chapter it has identified that there is a need to explore multi-objective optimisation for generation of process plans for WEEE recycling activities which considers both environmental and economical factors. Such an approach should provide operational support to determine a sequence of recovery and recycling processes to be undertaken for eco-efficient recycling of individual products in WEEE. The implementation of such systematic approach to developing bespoke recycling process plans for various products, together with parallel consideration of ecological and economical impacts of WEEE recycling form the core of the research reported in this thesis, as outlined in chapter 7 and 8.

Chapter 5

Review of Manufacturing Process Planning and its Approaches

5.1 Introduction

This chapter provides a brief review of process planning functions used as part of design and manufacturing activity to reduce cost and improve quality. The initial sections of the chapter provide an overview of manufacturing process planning and its significance to the substantial improvements witnessed in the manufacturing industry. A classification of approaches to process planning is then provided along with a description of the traditional approaches to manual process planning. The later sections of the chapter justify the need for Computer aided Process Planning (CAPP) and describe the different approaches to CAPP. The strengths and weaknesses of these approaches in terms of the requirements of recycling process planning of WEEE are then evaluated. The chapter concludes by selecting an appropriate process planning approach to be used for recycling process planning.

5.2 Manufacturing Process Planning

A large number of new technologies have been implemented in the manufacturing industry throughout the world. Process planning has been one of these technologies and is virtually performed in all manufacturing industries (Zhang and Alting 1994). Manufacturing process planning has been instrumental in improving the efficiency in small-batch, discrete part, metal fabrication industries. However, recently process planning has also been identified to play an important role in other manufacturing and process industries, such as food manufacturing industries, electronics manufacturing industries, furniture manufacturing companies (Mousavi *et al.* 2007), or even chemical process plants (Liu and Sahinidis 1997). A process plan plays an important role in production management. It can be used for the assurance of product quality and the optimisation of production sequencing. The process plan can even be used to determine the layout of the machines on the shop floor. Recent research has demonstrated that

process planning plays an important role in Flexible Manufacturing Systems (FMS) and Computer Integrated Manufacturing (CIM) enterprises (Wang *et al.* 2007).

According to the Society of Manufacturing Engineers, process planning is "*the systematic determination of the methods by which a product is to be manufactured economically and competitively*" (Alting and Zhang 1989). Chang and Wysk (1984) defined process planning as "*the act of preparing detailed operation instructions to transform an engineering design to a final part*". Generally, manufacturing process planning refers to either machining process planning or assembly process planning. Machining process planning is concerned with how each single part is machined, whereas assembly process planning is concerned with how several parts can be assembled together to manufacture a product. The definition of process planning as adopted by this research is the 'selection and sequencing of operations to transform a chosen raw material into a finished component'. Usually a process plan contains the route, processes, process parameters, machines and tools required for production. However, when used in different industries, the process planning functions may involve several or all of the following activities:

- Selection of machining operations
- Sequencing of machining operations
- Selection of cutting tools
- Selection of machine tools
- Determining setup requirements
- Calculation of cutting parameters
- Tool path planning
- Design of jigs and fixtures

The degree of detail incorporated into a typical process plan depends on the type of parts, production methods, and documentation needed. The process planning activity has traditionally been experience-based and has been performed manually. However as the production gradually moved towards automation, the need for dynamic responses, fast plan generation, and smooth interface between design and manufacturing became essential in operating the new manufacturing systems. Thus, the automation of the

process planning has become critical. A classification of approaches to manufacturing process planning and their description is given in the following sections.

5.3 Approaches to Process Planning

There are two basic methods employed in process planning namely the manual process planning and computer aided process planning (Zhang and Alting 1994). Manual process planning can be broken into two distinctive approaches, the traditional approach and the workbook approach (Allen 1987). The computer aided process planning can be further categorised as the variant approach to CAPP and the generative approach to CAPP (covered in section 5.5). Figure 5.1 illustrates a hierarchical classification of different approaches to process planning.

5.3.1 Traditional Approach

The traditional approach to manual process planning involves examining the information of a part design described in the form of a blueprint, identifying similar parts (from memory), and manually retrieving process plans for these similar parts.

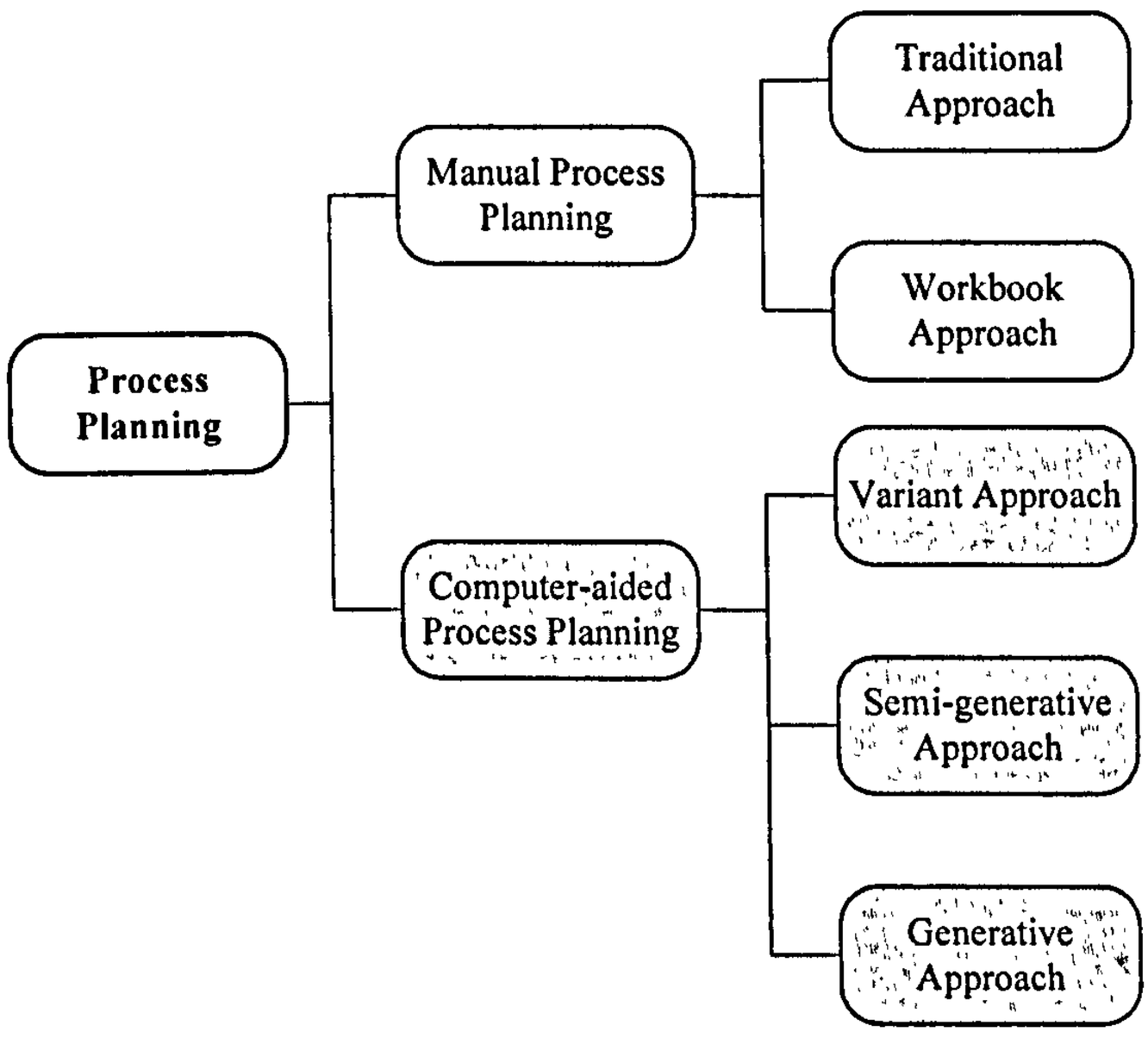


Figure 5.1: Classification of approaches to process planning

Referral to manuals to ascertain the company's recommended tools, feeds and speeds is then followed by creation of a new process plan through modifying and adapting an old process plan to meet the requirements of the new blueprint.

5.3.2 Workbook Approach

An alternative and more efficient approach to manual process planning is the workbook approach. It involves cataloguing sequences of operations for given families of workpieces. The pre-determined sequence can be quickly assessed by the process planner to develop a new process plan. The catalogue allows for greater consistency in process planning and provides the process planner with greater functionality. On the other hand, this method is limited by the number of variables including materials, machines, geometry and quality etc that can be catalogued. As the variety increases the number of possible permutations and pages in the workbook also increase exponentially. The workbook approach like the manual method is a subjective function, based on the experience of the planner, his/her personal preference, extent of shop knowledge, interpretation of design requirements and many judgmental factors (Chryssolouris 2005).

5.3.3 Advantages and Disadvantages of Manual Process Planning

Scallan (2003) noted that the real advantage of manual process planning is its low cost and flexibility. However, there are a number of distinct disadvantages as well, including:

- ***Lack of consistency in planning:*** There are many ways to manufacture even a very simple component. The plan developed for any given component reflects the process planner's knowledge, experience and personal choice. Different planners might manufacture the same component in a completely different way.

- ***Late design modifications:*** Manual process planning is not very responsive to late design changes due to its labour intensive nature.

- ***Excessive clerical content:*** The paperwork generated by manual process planning is excessive which highlights an inefficient use of engineering staff. The process can also become very labour intensive.

- ***Changing technology:*** Manual process planning requires continual re-education of production engineers about the changing manufacturing environment, the introduction of new processes and the withdrawal of obsolete equipment.

5.4 Computer Aided Process Planning

Zhang and Alting (1994) defined CAPP as the functions which use computers to assist the work of process planners. The level of assistance depends on the various strategies employed to implement the system. In some applications, computers are only used for data storage and retrieval so process planners can manually construct their plans. In slightly more advanced applications, computers are used to automatically generate basic process plans for simple workpieces. Process planners are still required in these instances to provide some sort of data input as plans often need slight ad hoc modifications to fulfil specific requirements. The next generation of CAPP involves the generation of process plans by computer alone, which may replace the need for a process planner when their knowledge and expertise can be effectively incorporated into a computer program.

Niebel (1965) first presented the idea of using the speed and consistency of the computer to assist in the generation of process plans. Schenk (1966) then discussed the feasibility of automated process planning. CAPP was not broadly addressed until the beginning of the 1970s due to the fact that computer capabilities of both hardware and software were limited. Since then tremendous advancements have been made in the development of CAPP systems. A number of research reviews for CAPP were reported in Alting and Zhang (1989), Ham and Lu (1988), Weill *et al.* (1982) and Wysk *et al.* (1985).

5.4.1 Advantages and Disadvantages of CAPP

As a result of the tremendous efforts that have been made in the development of CAPP systems, computer aided techniques are now a common place in manufacturing. The task of carrying out the detailed process plans that has traditionally been done manually is mostly computerised now. CAPP is aiding most manufacturing companies to solve their problems of automating process planning and overcoming the increasing shortage of skilled process planners. The other advantages of CAPP systems are considered to be:

- ***Time savings:*** By using CAPP as opposed to manual process planning time savings range from days to minutes. Lead times are reduced and manufacturing flexibility is increased due to the ability of reacting quickly to new or changing requirements. The amount of paper work and clerical effort involved in CAPP is far less than with manual process planning.

- ***Improved productivity:*** More efficient use of machines, tooling, material, and labour is realised by using CAPP and "Best practice" can be documented for consistent application throughout the organisation, rather than captured mentally in the manual process planning by the process planner.

- ***Lower production cost:*** Productivity improvements through computerised process planning also result in the reduction of production costs. Additionally, the skill level required to produce computerised process plans is less than that required for manual methods.

- ***Improved Consistency:*** CAPP assures consistent application of planning criteria. Also, the number of errors generated during manual process planning is reduced.

- ***Rapid integration of new production capabilities:*** With the rapid changes in manufacturing capabilities, maintaining a competitive advantage requires fast integration of new production processes. Computerised process planning allows process plans to be quickly updated to include new production processes and technologies.

It should also be noted that, there are several problems associated with CAPP (some of which are outlined below) which need to be considered when pursuing the computerised route of process planning. For example, in order to fully automate process planning, the part features must be extracted from the product model without human intervention. However, engineering drawings sometimes do not convey all the information about a part as information contained in them can be inaccessible or in a form incompatible with CAPP. In addition, different Computer Aided Design (CAD) systems have different methods of representing dimensions and other part properties. This makes the interface

between CAD and CAPP systems, where part features are translated into a CAPP recognisable form, another source of error for computerised process planning systems. The designer is often unaware of potential manufacturing constraints and may produce a design that is either infeasible or too costly to produce. Finally, process plan monitoring, security and improvements can become highly complex and difficult in the cases where generation and execution of a computerised process plan take a long time, and may involve several manufacturing organisations in different geographical locations.

5.5 Computer Aided Process Planning Approaches

Two approaches to computer aided process planning are traditionally recognised, namely the variant approach and the generative approach (Zhang and Alting 1994). The superiority of any one approach can only be assessed in terms of specific requirements. The variant and the generative approach to CAPP along with their suitability for recycling process planning are evaluated in the following sections.

5.5.1 The Variant Approach

The variant approach to process planning was the first approach used for CAPP. This approach is based on the concept that similar parts will have similar process plans. It is similar to the traditional manual approach to process planning where a process plan for a new part is created by recalling, identifying, and retrieving an existing plan for a comparable part, and making the necessary modifications for the new part (Alting and Zhang 1989). To implement variant approach to CAPP, group technology based on part coding and classification is used. Part families are created of parts having common attributes to group them into a family. A standard plan to manufacture the entire family is then created and stored for each part family.

According to Chang (1990), the development of a variant process planning system has two stages, namely the preparatory stage and the production stage (as depicted in Figure 5.2). In the preparatory stage, existing parts are coded, classified, and later grouped into families. The standard plan is structured and stored in a coded manner using operations codes. Once the coding, classification, family formation, and standard plan preparation is completed, the production stage becomes ready to produce new process plans.

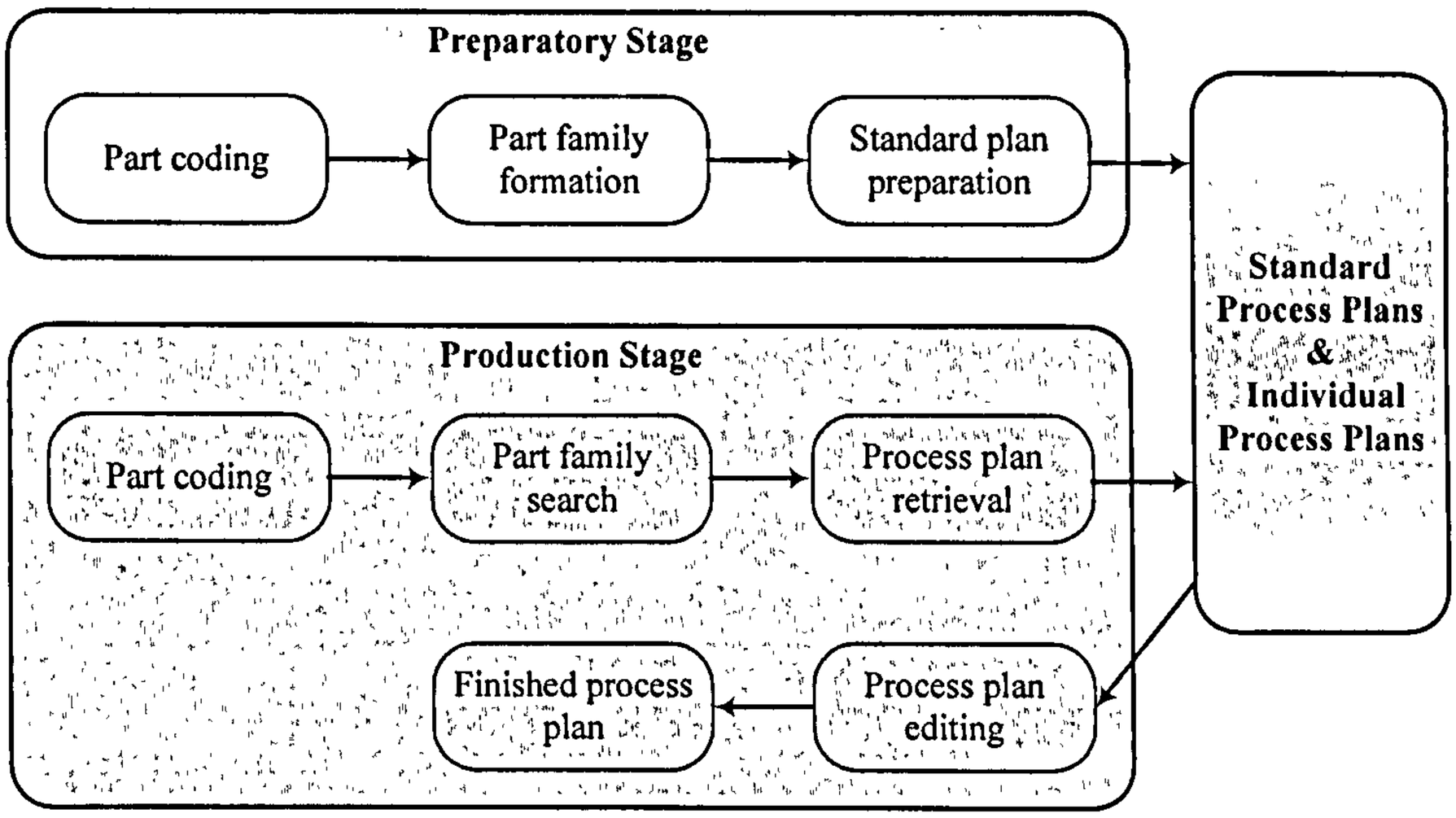


Figure 5.2: Variant process planning approach (Chang 1990)

In the production stage, generation of a new process plan starts with coding an incoming part. The code is then sent to a part family search routine in order to find the family to which it belongs. Since the standard plan is indexed by family number, it can be easily retrieved from the database and modified to suit the new part. As the standard plan is designed for the entire family rather than for a specific part, the editing of the plan is unavoidable. However, in variant approach the planner accomplishes 70 - 80% of the planning work involved in generating a process plan for a new part by using the standard plans.

Alting and Zhang (1989) noted that the variant approach is highly advantageous in increasing the information management capabilities. Complicated activities and decisions require less time and labour in the variant approach. Process planning systems based on variant approach allow procedures to be standardised, hence, incorporating a planner's manufacturing knowledge and structuring it to a company's specific needs. Therefore, variant systems can organise and store completed plans and manufacturing knowledge from which new process plans can be quickly evaluated. However, several problems are also associated with variant approach. There are difficulties in maintaining consistency in editing practices, and inability to adequately accommodate various combinations of geometry, size, precision, material, quality, and dynamic shop loading. The quality of process plan also depends on the background knowledge of the process planner.

5.5.2 The Generative Approach

The generative approach to CAPP automatically synthesises a process plan for a new component. The ultimate goal in the generative approach is the creation of the process plan from information available in a manufacturing database without human intervention. However, the definition of the generative approach to process planning used in industry is somewhat relaxed and the systems which contain some decision making capability on process selection are considered generative. Process plans in generative approach are generated by means of decision logics, formulae, algorithms, and geometry based data to perform uniquely the many processing decisions for converting a part from raw material to a finished state (Alting and Zhang 1989). For generative systems, input of the part description forms a major part of the information needed for process planning. As the aim in the generative approach is to automate the system, the part description should be in a computer readable format.

Although, the generative approach is complex and a generative CAPP system is difficult to develop, the rapid development of Artificial Intelligence (AI) techniques has greatly encouraged the utilisation of the AI techniques in process planning. This kind of system is mostly oriented toward large companies and research organisations since they can afford the investment on a long term project. The major advantages of generative process planning are the rapidity and consistency with which plans can be generated and ease of incorporating new processes, equipment, methods, and tooling into the plans. In addition, the new components can be planned as easily as existing components.

5.6 Suitability of CAPP for Recycling Process Planning

Process planning in manufacturing applications is a highly established field which comprises the selection and sequencing of processes and operations to transform a chosen raw material into a finished component in discrete part manufacture. CAPP has nowadays become common place in most applications and is preferred over the traditional manual process planning to introduce consistency in planning. Due to the broad range of products in WEEE and a wide variety of recovery and recycling processes involved in the end-of-life management of such waste, computerised process planning is

found to be more suitable to be used for recycling process planning than manual process planning approaches.

Among the approaches to CAPP, generative approach is based on developing a completely new process plan for every part. It uses the decision logic, formulae, algorithms and geometric analysis and is considered to be the best approach for complex manufacturing process planning. On the other hand, the variant approach is similar to the manual process planning as it retrieves an existing standard plan and modifies it to suit the given product. This standard plan is usually for a complex product that incorporates all the features for a particular group or family of products. The process plan for the product under consideration can be compiled by retrieving those processes in the standard plan that are relevant and grouping them to generate a customised process plan for the product.

In the case of recycling process planning for WEEE, nature and range of processes is not as complicated as in manufacturing. Furthermore, there is a significant potential for the reuse of the recycling process plans as WEEE contains families of electrical and electronic equipment having products, parts and components commonality among different products. It is envisaged that the adaptability and flexibility of the variant process planning makes such approach particularly suitable for the recycling process planning. Therefore based on the product categories (or families) covered in the scope of the WEEE directive, a variant-based approach to recycling process planning is developed in this research.

5.7 Chapter Summary

This chapter has provided an overview of different approaches to manufacturing process planning, and has highlighted the main literature considering their comparative merits. This review is intended to evaluate the suitability of different approaches to process planning to provide a foundation on which the most appropriate approach can be selected for use within recycling process planning framework to be developed in this research. Based on this review it has been concluded that variant approach to CAPP is the most suitable approach for recycling process planning. The adoption of this approach as part of recycling process planning framework will be described in Chapter 7.

Chapter 6

Research Methodology

6.1 Introduction

This chapter describes the research methodology used in undertaking the research reported in this thesis. It begins with a brief description of the four defined stages of the methodology before each stage is detailed. These stages include the initial review of literature together with the corresponding refinement in the research hypothesis, and the development of an integrated recycling process planning framework together with an associated ecological and economical assessment methodology. The chapter concludes by describing the final two stages which involves experimentation through development of the prototype recycling process planner and the associated case studies, and finally the analysis of the results to develop the research conclusions.

6.2 A Brief Overview of Research Design Methodology

Research is the process of making claims and then refining or abandoning some of them for other claims more strongly warranted (Creswell 2003). There are a number of different research design methods being used for management, social sciences and engineering (e.g. Scientific method, analytical method, imperial method, survey method, action research, case study research, quasi-experimental etc.). Most commonly these research methods are classified into three research methods, namely quantitative, qualitative and mixed.

A quantitative method involves the use of post positivist claims for developing knowledge, use of strategies of inquiry such as experiments and surveys, and collection of data on predetermined instruments. Quantitative methods are further classified into deductive (inferences from general principles), inductive (from facts to hypothesis to conclusions) and model building (Hong 2005). On the other hand, a qualitative method involves inquirer making knowledge claims which are based primarily on constructivist perspectives and uses narrative, phenomenologies or case studies. The mixed method

involves researcher making knowledge claims on pragmatic grounds (e.g. consequence-oriented, problem-centred, and pluralistic) and employs strategies of inquiry that involve collecting data either simultaneously or sequentially to best understand the research problems (Creswell 2003). The research methodology adopted by this thesis is closely related to mixed method research, and is further described in the next section.

6.3 Research Methodology

The research methodology adopted in this thesis is based on a conventional research approach beginning with the definition of the research hypothesis, followed by the review and survey of relevant academic research and industrial practice, definition of research aims and objectives, theoretical development of research activities together with experimentation and demonstration of research concepts through a number of case studies, and analysis of research results. The various stages in the research methodology are depicted in Figure 6.1.

The initial research assertion and hypothesis were formulated through author's prior knowledge of the subject area. This knowledge was then augmented by an extensive survey of literature in WEEE recovery and recycling, end-of-life product recovery and operations management in recovery environments, and process planning approaches alongside a number of industrial visits to actors within the WEEE recovery chain. This allowed a detailed review of the academic developments in the WEEE recovery and recycling sector as well as the reflection of the practical issues within the recovery sector. The initial assertion and hypothesis were then refined based on this expanded knowledge, and the aims and objectives of the research were defined.

Establishment of the research hypothesis together with the aim, objectives, and scope of the research moved the research undertaken in this thesis into its second phase. A novel recycling process planning framework was developed based on the research objectives to plan the recovery and recycling processes to be used for the recycling of individual products in WEEE. The framework allows the utilisation of new knowledge to improve the end-of-life management of WEEE. Initially the recycling process planning was only based on the characteristics of the product being recycled.

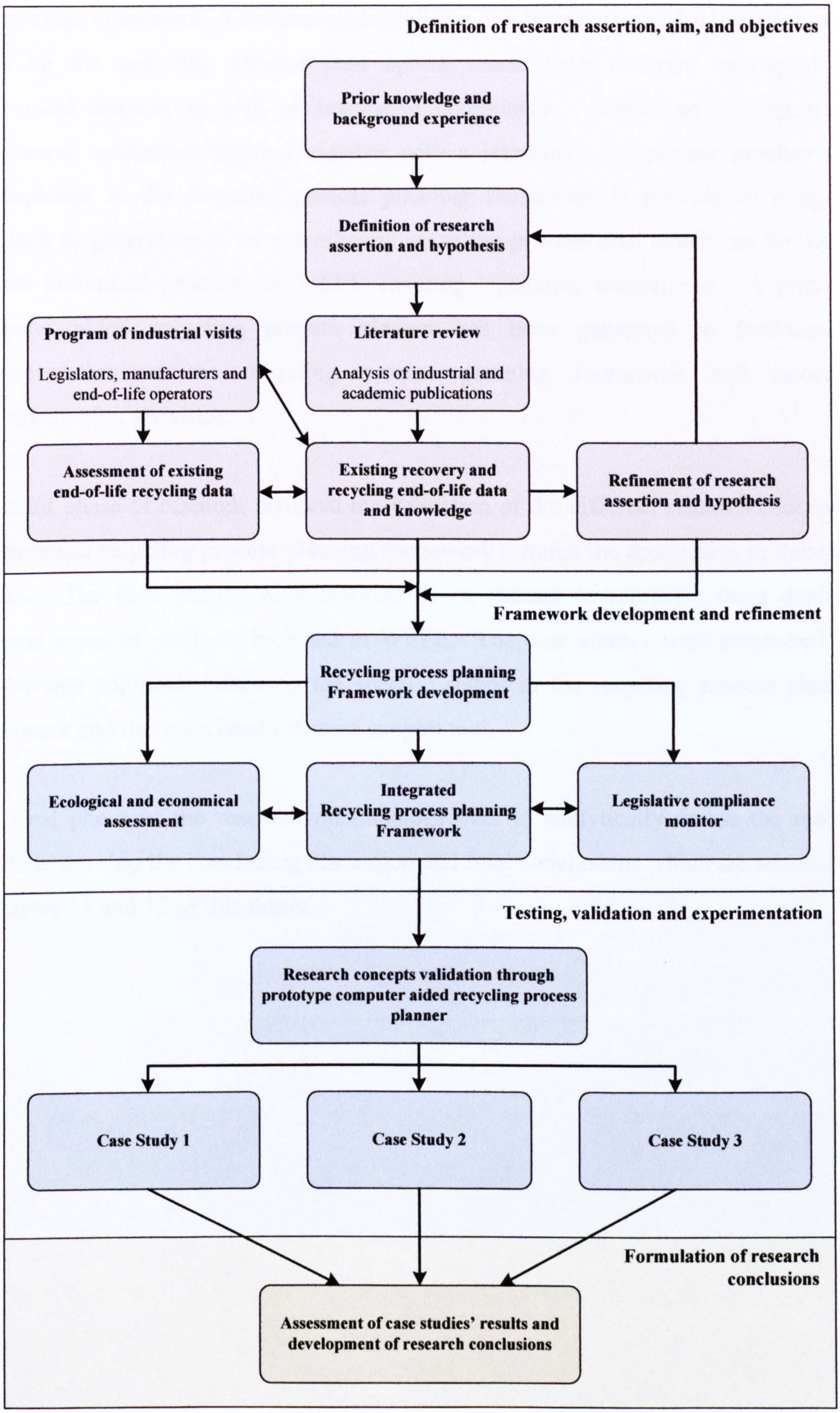


Figure 6.1: Research methodology used within the thesis

At this stage of research, it became apparent that a number of possible end-of-life options including the recycling process plan option would have different ecological and economical impacts as well as legislative compliance. Hence, an ecological and economical assessment method together with a legislative compliance monitor were encompassed in the recycling process planning framework to provide an integrated approach to generation of an eco-efficient recycling process plan which can be used to recycle individual products in WEEE ensuring legislative compliance. A prototype computer aided recycling process planner has been generated to facilitate the implementation of the recycling process planning framework and associated experimentation activities.

The third phase of research involved the validation of the different research concepts in the proposed recycling process planning framework through the application in three case studies. The case studies were selected in an attempt to represent three distinctly different types of products included in WEEE. The case studies were conducted in a step-by-step approach following the specific stages in the recycling process planning framework and the associated software support tool.

The final phase of the research methodology was to analytically assess the research results to develop the concluding discussion and final conclusions which are summarised in chapter 11 and 12 of this thesis.

Chapter 7

An Integrated Framework for Recycling Process Planning

7.1 Introduction

This chapter presents a framework to produce bespoke recycling process plans for various products within WEEE. This framework consists of four stages, namely; product evaluation, legislative compliance monitor, recycling process planning and an ecological and economical assessment. The chapter begins by highlighting the benefits of using the recycling process planning in the end-of-life phase of WEEE. The Integrated Recycling Process Planning framework is then presented along with a description of each of the four stages involved in this framework.

7.2 Recycling Process Planning for WEEE

The current ad hoc applications of WEEE recycling, which are mainly based on the capabilities and available resources within the recovery facilities, are highly ineffective in terms of both ecological and economical considerations. The determination of environmentally-friendly and economically-justifiable recycling routes for WEEE is a complex problem. It involves concurrent consideration of product and process related end-of-life issues. Product related end-of-life issues involve a wide range of products with varying material compositions, weights and product structure as well as the source of the product, its age and condition. Similarly, process related end-of-life issues involve a wide range of different end-of-life technologies and recycling processes, as well as their environmental and economical impacts. Though the separation of ferrous and non-ferrous metals by their properties has been highly successful and lucrative for the recovery industry for over half a century, a substantial amount of fractions included in WEEE consisting of non-metallic materials such as plastics, rubbers, textiles, wood and glass, are still destined for landfill.

The end-of-life processing of WEEE can broadly be divided into three areas, the de-pollution of electrical and electronic equipment, the dismantling of materials and

components of interest, and the post-fragmentation separation of the remaining shredded product. This research has identified that where information about product being recycled is unknown, treatment facilities face difficulties in conducting the appropriate recycling. Consequently, majority of WEEE in these recycling facilities is processed without proper depollution, resulting not only in hazardous and toxic substances polluting the environment together with secondary material streams but also in non-compliance to the legislation. Access to the design information, which can facilitate product recycling, is not available to recyclers. Hence, there is a need to evaluate the product for collecting information required as part of the recycling process planning. The manual disassembly of valuable parts and contaminating materials has never been attempted by the majority of WEEE recovery facilities mainly due to the lack of product information as well as awareness among recyclers about the potential value of reuse through repair and refurbishment. Timely dismantling and processing of these materials and components included in electrical and electronic equipment has the potential to improve the eco-efficiency and legislative compliance of WEEE recycling

In addition, the recently introduced WEEE and RoHS directives are set to control the nature and range of recycling processes used for the processing of WEEE, and therefore influences the planning of the recycling activities. These directives require the stringent pre-treatment requirements along with demanding recovery and recycling targets to be met across ten categories of electrical and electronic products. Therefore, before implementation of any recycling process planning, there is a need to assess its compliance with appropriate legislation.

Finally, an assessment of the ecological and economical impacts of WEEE recycling in different end-of-life options including the recycling process plan option is also needed to support the decision-making in selecting the most eco-efficient recycling routes for individual products in WEEE. The above discussion highlights the need for a systematic approach for planning of recycling activities for WEEE. These are included as various stages of a recycling process planning framework generated in this research and are described in the following sections.

7.3 An Integrated Recycling Process Planning Framework

An end-of-life product may be discarded to landfill, incinerated, disassembled for material reclamation, collected and examined for possible refurbishment and reuse, or indeed a combination of these activities may occur. Each end-of-life option incurs economical and environmental costs and creates potential value. There are many factors that influence the selection of the most appropriate end-of-life strategy including environmental impact, legislative compliance, market competition and the impact on brand image, product design complexity and material composition. The integrated recycling process planning framework presented in this chapter aims to assist designers, manufacturers, and recovery and recycling facilities in determining a bespoke end-of-life recycling process route for an individual product (or product family) in WEEE. It is argued that such a systematic approach to developing a bespoke recycling process plan minimises the environmental impacts of end-of-life management in a technically feasible way and at a reasonable cost. The Recycling Process Planning (RPP) framework consist of four stages, namely a product evaluation, a compliance monitor, a recycling process planner, and an ecological and economical assessment, as depicted in Figure 7.1.

The activities within the RPP framework start with the product evaluation stage to identify the components of interest and the material composition within the product (see Figure 7.2). This product information is then used to identify the various requirements for legislative compliance and specific pre-treatment processes. Subsequently, a recycling process planning stage generates the specific product recovery and recycling processes to suit a particular electrical and electronic product scenario. Finally, the ecological and economical assessment stage analyses the end-of-life processes proposed by the RPP framework to gain an insight to the environmental and economical impacts associated with the recycling process plan. The tasks involved in each stage of the RPP framework are described in more detail in the following sections.

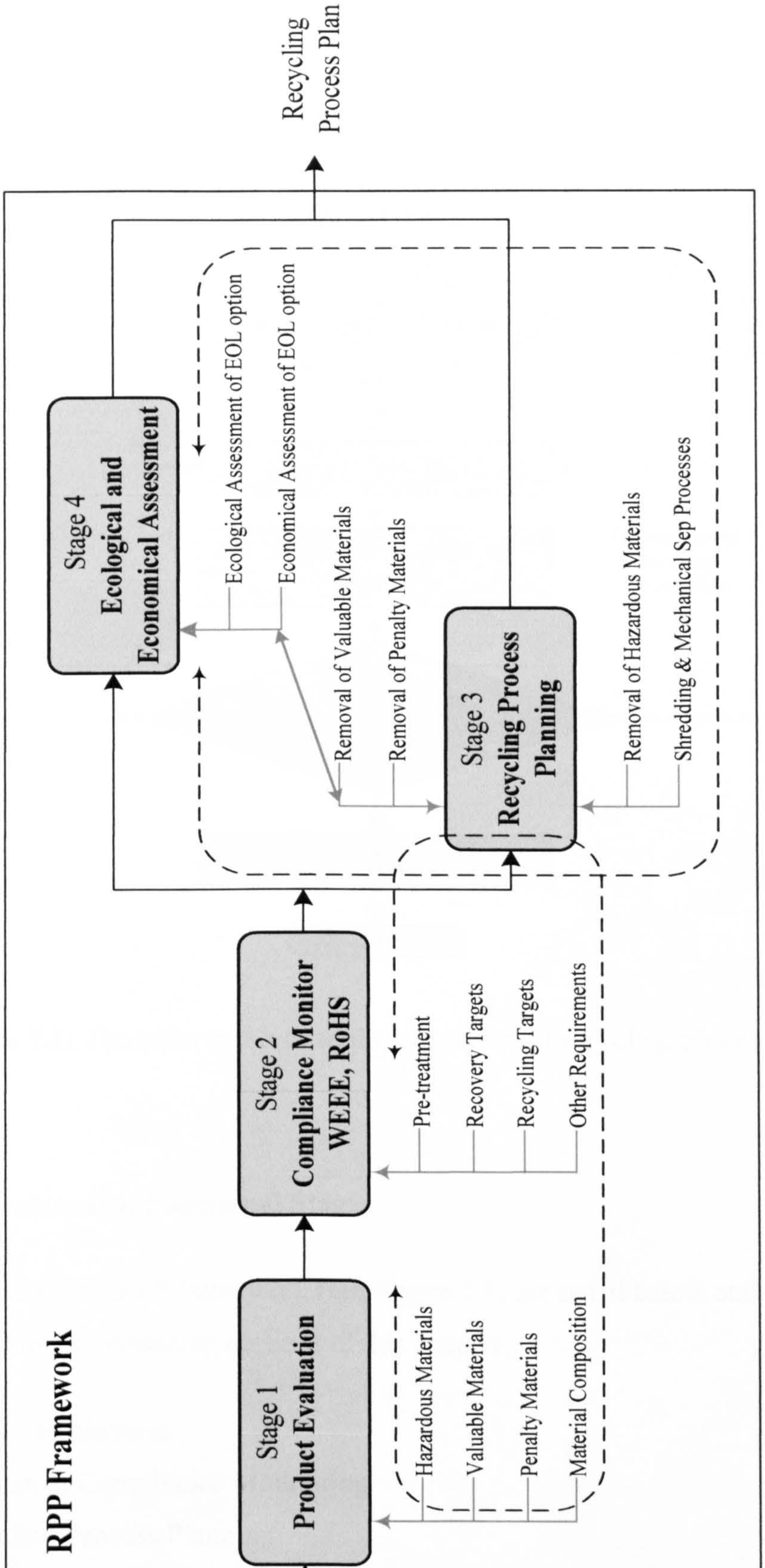


Figure 7.1: The integrated recycling process planning framework

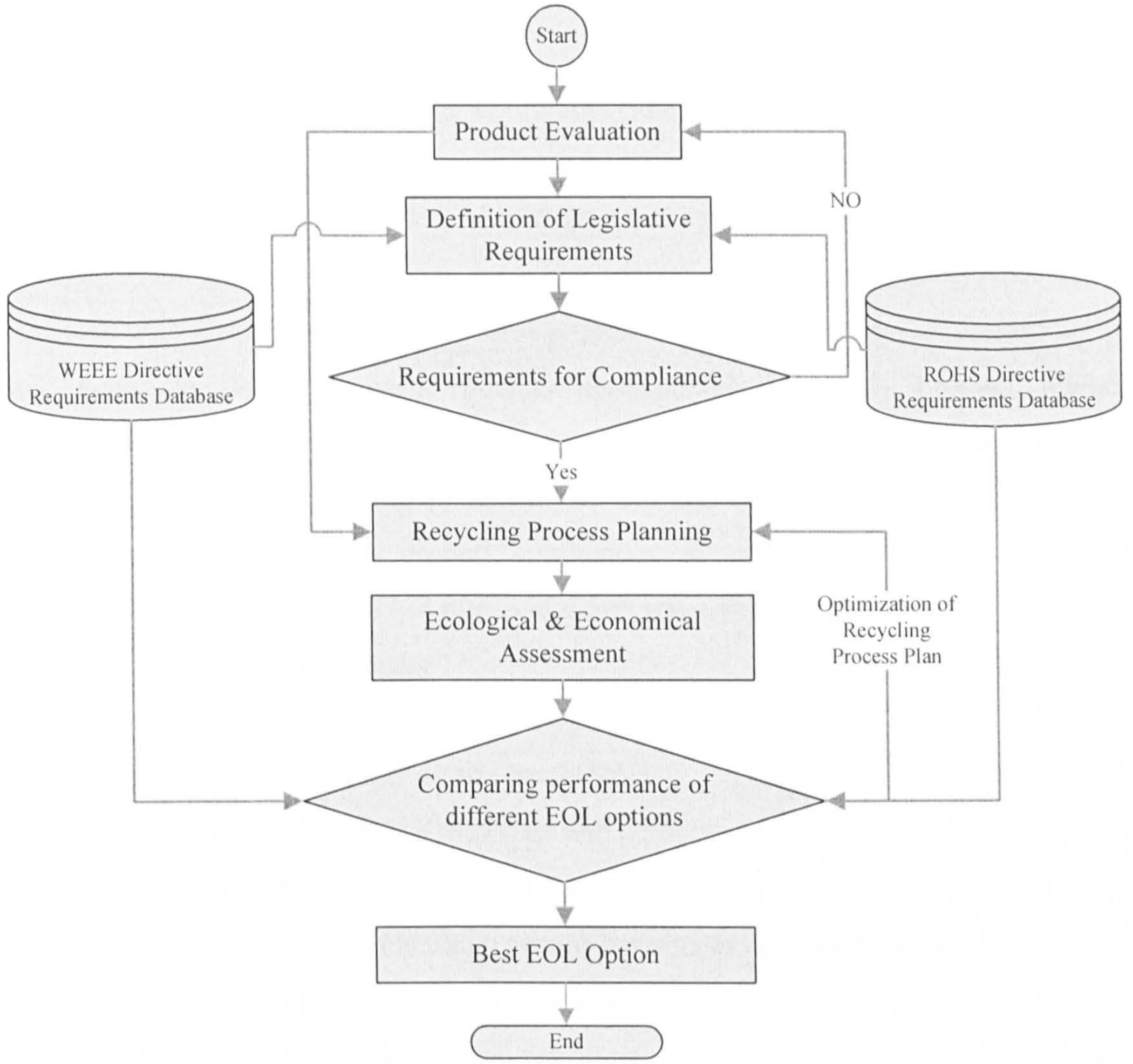


Figure 7.2: The tasks involved in the generation of recycling process plan

7.4 RPP Framework Functional Stages

The four stages of the RPP framework (see Figure 7.1) are listed below and are discussed in more detail in the remaining sections of this chapter.

1. Product Evaluation
2. Legislative Compliance Monitoring
3. Recycling Process Planning
4. Ecological and Economical Assessment

7.4.1 Product Evaluation

The aim of product evaluation stage is to collect the required product information to be used in recycling process planning. In case of process planning in manufacturing, the required information is readily available through design together with part and product drawings. This is in not the case in recycling process planning. Typically, information associated with product which can be used to plan its end-of-life route, i.e. hazardous and toxic materials, valuable parts, penalty materials and overall product material composition is not known to the recyclers. At present, in most cases access to initial product design is not available or restricted, and this absence of "readily available" information is one of the biggest hindrances in adopting effective end-of-life management for WEEE. The product evaluation stage bridges this information gap and consists of the following six tasks.

i. Identification of the product and its category
ii. Identification of hazardous materials and components
iii. Identification of valuable materials and components
iv. Identification of contaminating (penalty) materials and components
v. Identification of product's material composition
vi. Identification of the safe disposal processes

7.4.1.1 Identification of the Product and its Category

Product evaluation starts by identifying the end-of-life product and its category according to Annex 1A of the WEEE directive. This information is crucial to establish the legislative requirements for the product and is used in the subsequent stages of the RPP framework to determine the choice of the recovery options available for the product. An indicative weight is assigned to the product that can be used in calculating the recovery and recycling rates in different end-of-life options.

7.4.1.2 Identification of Hazardous Materials and Components

The second task in the product evaluation stage identifies the hazardous and toxic substances present in the product. This evaluation is essential for the selection of appropriate pre-treatment processes in order to comply with the requirements of Annex

1B of the WEEE directive related to the treatment of hazardous materials. Electrical and electronic products contain a wide variety of hazardous and toxic materials. Table 7.1 highlights the range and varying quantities of hazardous materials for a subset of products in WEEE. As different products in WEEE contain different hazardous and toxic substances, the systematic identification of such materials in each product is an indispensable task in the end-of-life management.

7.4.1.3 Identification of Valuable Materials and Components

The third task in the product evaluation stage identifies the valuable materials and components present in the product. In the practice of recycling of WEEE, selective disassembly (dismantling) is an indispensable process since not only the removal of hazardous components is essential but also the reuse of components has first priority as it aims at conserving the energy utilised in the production of product parts and components during the manufacturing phase. Figure 7.3 highlights the various valuable materials and components found in electrical and electronic equipment. Therefore, the identification and removal of valuable and reusable components before destructive disassembly can improve the eco-efficiency of product recycling.

Hazardous Materials	Refrigerator (kg)	Washing Machine (kg)	Toaster (kg)	Television (kg)	Kettle (kg)
Cooling	0.25	x	x	x	x
Insulation	0.3	x	x	x	x
Cathode ray tube	x	x	x	18	x
Fluorescent lamp	x	x	x	x	x
Thermostat	0.25	0.3	0.002	x	x
Batteries	x	x	x	x	x
CFC, HCFC, HCF, HC	0.5	x	x	x	x
External electric cable	0.20	0.3	0.02	0.15	0.15
Refractory ceramic fiber	x	x	x	x	x
Radioactive substance	x	x	x	x	x
BFR Plastics	1	0.75	0.3	2.4	x

Table 7.1: Hazardous materials and components in typical WEEE

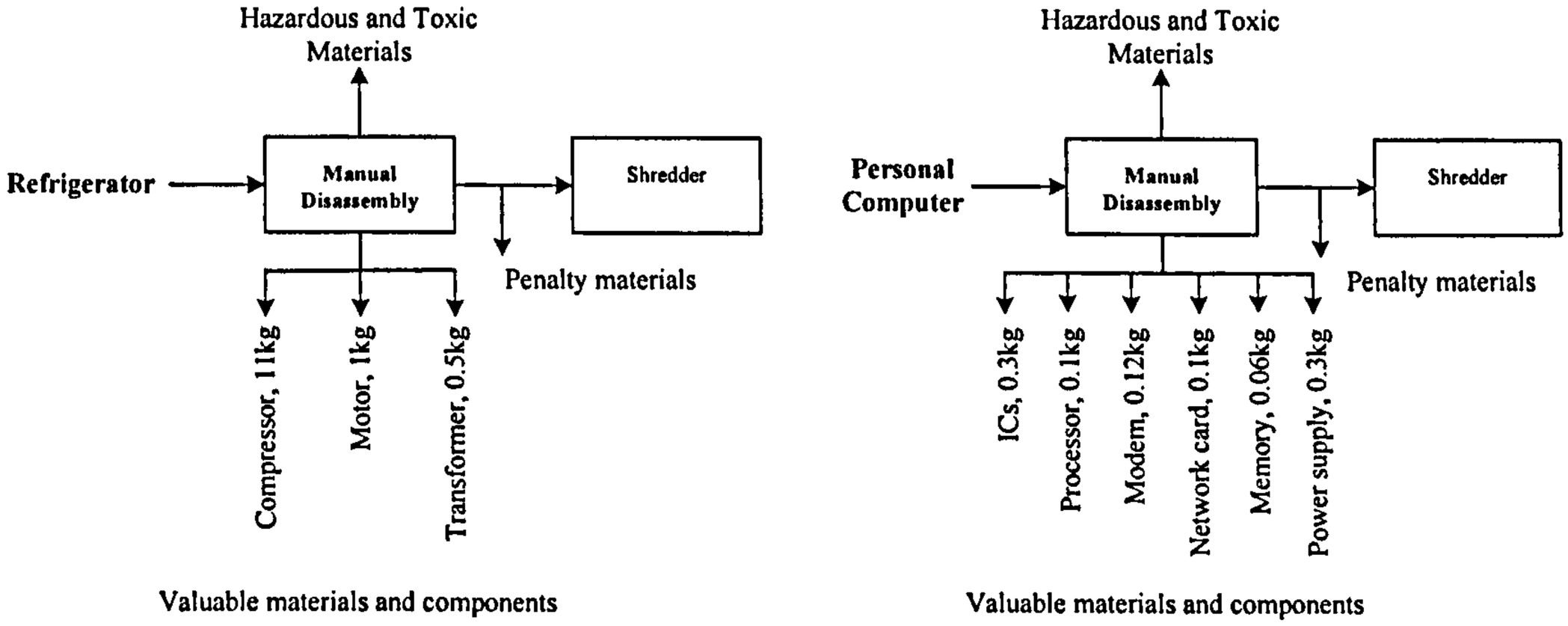


Figure 7.3: Valuable materials and components in typical WEEE

An extensive database containing information about different valuable materials and components included in various electrical and electronic products supports this evaluation task

7.4.1.4 Identification of Contaminating (Penalty) Materials and Components

The fourth task in the product evaluation stage identifies the penalty materials present in the product. Inefficiencies in the current shredding and separation processes are responsible for contamination of these penalty materials in post-fragmentation material streams.

Table 7.2 outlines some of the penalty materials commonly found in WEEE and their implications on post-fragmentation recovery. In addition, similarities in physical properties between penalty materials and target materials and their tendency to entangle with other materials make post-fragmentation separation processes less efficient. As the value of many post-fragmentation material streams depend on the material purity, identification and removal of these contaminating materials before sending the product to the shredder can improve the subsequent material recovery and economical performance of product recycling.

7.4.1.5 Identification of Product's Material Composition

In the fifth task in product evaluation, material composition of the product is identified and the product hulk is divided into material streams such as ferrous metals, non ferrous metals, plastics, glass etc

Penalty Materials	Implications on post-fragmentation recovery
Concrete	Problems in heavy medium separation
Textile	Entanglement with wires, Problems in air separation
Wood	Dense media separation unable to separate wood
Polyvinyl chloride	Entanglement with other plastics
Copper	Contaminates scrap steel, devalues the price of scrap steel
Cables	Entangle with other materials and screens

Table 7.2: List of penalty materials found in WEEE

Different categories of electrical and electronic equipment included in the WEEE directive differ in material composition. In addition, there are substantial differences between the material compositions of various products in the same category. It is, therefore, imperative to know the material composition before planning the recycling processes for a particular product. The information about the material content of a product captured in this task allows generation of a suitable recycling process plan which is economically and environmentally justifiable.

7.4.1.6 Identification of the Safe Disposal Processes

The final task in the product evaluation identifies the processes for safe disposal (incineration and landfill) of the remaining parts and materials in the product hulk. Currently in most recovery and recycling applications, the inefficiencies of the mechanical separation processes and economic concerns over the available recycling technologies necessitate disposal of the product through incineration and landfill. The danger in landfilling specific parts and components included in WEEE lies in the formation of toxic furans. On the other hand, landfilling of WEEE carries a danger of leaching of hazardous substances and polluting the ground water. WEEE directive requires special arrangements to be undertaken at the designated landfill and incineration sites handling WEEE.

7.4.2 Legislative Compliance Monitoring

The second stage of the RPP framework identifies the legislative requirements related to the recycling of the product under consideration. The legislative compliance monitoring

stage starts by identifying whether the product under consideration falls within the scope of WEEE or RoHS directives. The WEEE directive requires specific treatment and recovery methods to be followed for individual products. For example, the removal of CRT from which the fluorescent coating must be removed, plastic containing brominated flame retardants and gas discharge lamps from which the mercury must be removed etc. Compliance monitoring ensures that the bespoked recycling process plan generated for the product caters for the depollution requirements for the product under consideration.

In addition to meeting the pre-treatment requirements, WEEE directive requires recovery and recycling targets ranging from 50% to 80% by product weight to be met across ten categories of electrical and electronic equipment. Similarly, the RoHS directive requires prevention of the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ether in electrical and electronic equipment. In the compliance monitoring stage, the detailed product information identified through product evaluation stage is utilised to assess the product characteristics against the WEEE and RoHS directives requirements. The legislative compliance information is then passed to the recycling process planning stage to assist with the selection of the appropriate recovery and recycling processes to be included in the recycling process plan for the product under consideration.

7.4.3 Recycling Process Plan Generation

The third stage of the RPP framework generates bespoked recycling process plans for individual products in electrical and electronic equipment. Process planning in manufacturing translates product design information into the process steps and instructions to manufacture a product efficiently and effectively. The recycling process planning stage aims to take advantage of the benefits provided by a systematic approach to process planning experienced in manufacturing applications and apply a similar principle to increase the efficiency of WEEE recycling activities.

As described in chapter 5, there are two basic approaches to computer aided process planning, namely generative and variant approach. The adaptability and flexibility offered through the variant approach makes it particularly suitable for recycling process

planning for WEEE. Figure 7.4 highlights the generation of recycling process plans using the variant approach.

In the recycling process planning stage based on the product categories used in the WEEE directive, a number of standard recycling process plans are developed and used for generation of bespoke recycling process plans for individual products in electrical and electronic equipment. The recycling process planning stage utilises the information from the product evaluation stage and legislative compliance monitoring stage to customise the standard recycling process plan into a bespoke recycling process plan for product under consideration. A standard recycling process plan mainly consists of the following five main operations:

- Depollution for legislative compliance
- Dismantling for value recovery
- Dismantling to remove penalty substances
- Shredding and mechanical separation to recover different material streams
- Disposal / Landfill

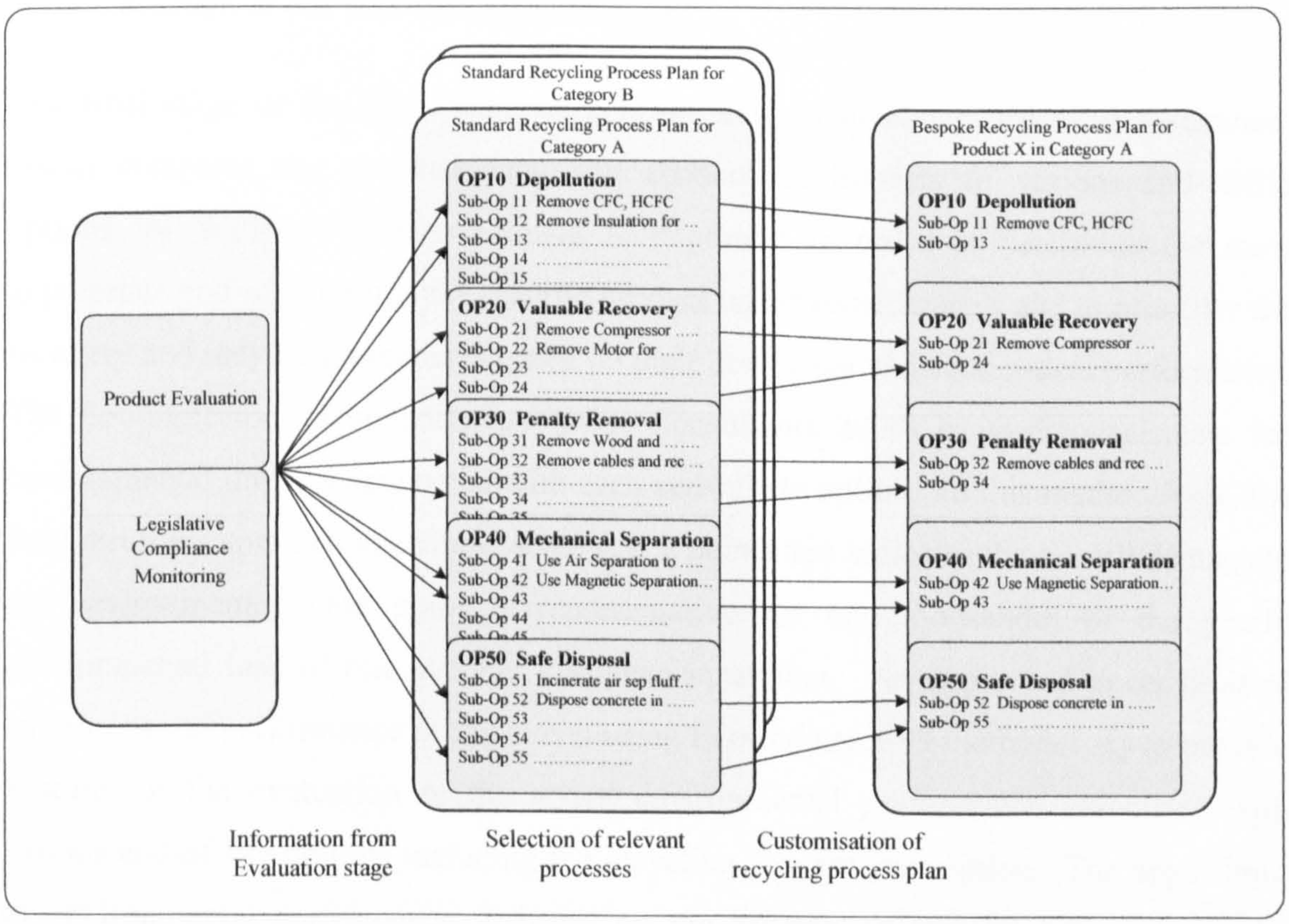


Figure 7.4: Generation of bespoke recycling process plan using a variant approach to process planning

Each operation in the bespoked recycling process plan consists of a number of relevant sub-operations i.e. specific recovery and recycling processes (see Figure 7.4). These processes are linked to different product design and material characteristics and legislative compliance requirements identified in the first and second stages of the RPP framework. For example in case of a refrigerator, the presence of insulation identified during product evaluation stage will trigger the addition of the specific recovery process related to the removal of insulation in the recycling process plan.

It is claimed that the utilisation of the recycling process planning allows for the adoption of different end-of-life strategies (reuse, refurbishment, material recycling, incineration and disposal) for different components and materials contained in a product to improve the overall performance of WEEE recycling. To validate this claim, the next stage of the RPP framework assesses the ecological and economical impacts of the recycling process plan option and compares theses results with the performance of other end-of-life options.

7.4.4 Ecological and Economical Assessment

The final stage of the RPP framework is the ecological and economical assessment which compares the environmental and economical impacts of various end-of-life options for WEEE. This assessment is important in order to determine the most appropriate end-of-life route for specific product under consideration and to prioritise the recovery and recycling processes based on their ecological and economical performance. The Eco-indicator 99 methodology (PRE Consultants 2000) is used to calculate the environmental impacts associated with each end-of-life option. In this methodology, the final result is expressed in a single score (i.e. a point) that indicates the overall damage to the environment. One point is representative for one thousandth of the yearly environmental load of one average European inhabitant. An upper and lower limit of environmental performance is calculated using Eco-indicator 99 methodology to provide a scale for the evaluation of the actual environmental performance associated with various end-of-life options including the recycling process plan option. The upper limit of environmental performance is based on the assumption that all materials can be recovered (zero landfilling) without any environmental burden whereas the lower limit of

environmental performance assumes all materials in the product will end up in the landfill.

A parametric cost/benefit approach is used to calculate the economical impacts associated with product recycling. An upper limit of economical performance related to hundred per cent recovery and recycling of all material contents and a lower limit of economical performance related to the cost of sending the complete product to landfill are defined and used to evaluate the actual economical performance associated with various end-of-life options including the recycling process plan option. Finally, the ecological and economical performance results are combined to aid the decision making involved in selecting the most suitable end-of-life recycling route for WEEE. The ecological and economical assessment is covered in more detail in chapter 8.

7.5 Chapter Summary

This chapter has outlined the RPP framework along with its four stages namely the product evaluation, the legislative compliance monitoring, the recycling process planning and the ecological and economical assessment. The current problems facing the WEEE recovery sector are addressed in the different stages of the RPP framework. An overview of this recycling process planning framework is also provided in an accepted journal paper which is included in *Appendix 2*. The framework further extends previous research on end-of-life management by considering optimal sets of trade-offs between environmental and economical variables and includes simultaneous consideration of the macro level end-of-life planning (product reuse, material recycling, disposal) and micro level end-of-life planning (pre-treatment and de-pollution, removal of valuable parts and penalty materials, shredding and separation processes). In order to support the application of this framework within the end-of-life management of WEEE, this research has generated a computer aided recycling process planner which aids the implementation of various stages of the RPP framework. The design and implementation of this prototype system is described in chapter 9.

Chapter 8

Ecological and Economical Assessment Methodology

8.1 Introduction

The RPP framework described within the previous chapter highlighted the need to assess the ecological and economical impacts of different end-of-life options for WEEE. This chapter highlights the benefits of such an assessment for the effective end-of-life management of WEEE and presents a methodology to calculate the ecological and economical impacts associated with different WEEE recovery and recycling activities. The chapter begins by providing a rationale of using a holistic assessment in the end-of-life phase of WEEE. The Ecological and Economical (Eco^2) assessment methodology is then presented along with a description of various tasks involved in this methodology. Finally, a combined ecological and economical ranking method developed as part of author's research is described to provide a holistic understanding of the results of the Eco^2 assessment.

8.2 Rationale for Ecological and Economical Assessment

The end-of-life treatment of WEEE can be dealt with in different ways. Generally, there are six alternatives (end-of-life options) available for a product at its end-of-life as depicted in Figure 8.1. In terms of waste management hierarchy repair and reuse options are at the highest level, followed by remanufacturing option involving disassembly, inspection, part replacement, and technological upgrade (if needed). All of these options are considered beneficial from the environmental point of view since they extend the life of the product, thus avoiding any generation of waste. Unlike the end-of-life options mentioned above, in the recycling option the identity and functionality of used products and components are lost. The purpose of recycling based on the fragmentation process is to recover materials from end-of-life products and is increasingly considered to be more economically-viable than repair and remanufacture.

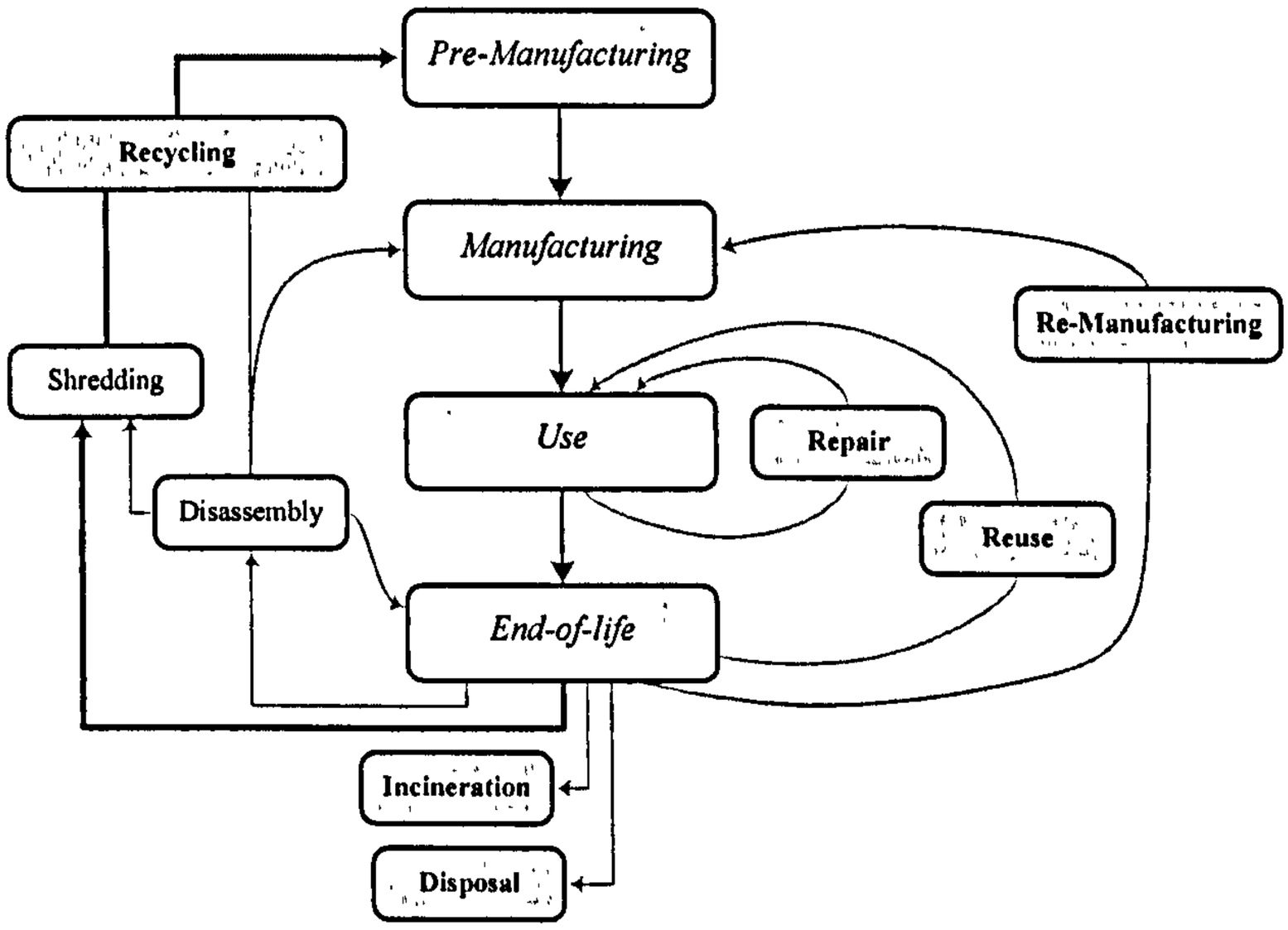


Figure 8.1: End-of-life options and their relation to product life cycle

Incineration of WEEE involves energy recovery and is less favourable than material recycling due to the loss of the material as a resource and the possible releasing of toxic gases into the environment. Disposal of the product to landfill as general waste is at the lowest level of the waste management hierarchy and causes the greatest environmental damage when compared to other end-of-life options. The wide range of products in WEEE and the complexity of materials in each product do not allow one end-of-life option to be generally applied to each product. As each end-of-life option involves varying amount of economical and environmental costs, selection of appropriate options for treating electrical and electronic equipment is of paramount importance for the effective end-of-life management of WEEE.

It became apparent following a review of industrial practices that the recovery treatment of WEEE has mainly been driven by economical considerations without any assessment of the environmental impacts of such recycling activities. The author argues that selection of the most appropriate end-of-life option for product recycling should not only be based on economic considerations, but also should take environmental impacts of end-of-life treatment into account as imposed by increasingly constraining legislation. This highlights the need for a systematic ecological and economical assessment methodology to aid the decision making involved in selecting the best possible end-of-life strategy for WEEE.

8.3 Ecological and Economical Assessment Methodology

The Eco^2 assessment methodology presented in this chapter is part of the RPP framework as depicted in Figure 8.2 and provides a systematic assessment approach to calculate the ecological and economical impacts associated with various end-of-life options for a product under consideration. This assessment is needed to identify not only which EoL option should be adopted but also extent to which the individual products in WEEE should be disassembled. The remaining sections of this chapter describe the tasks involved in the Eco^2 assessment methodology.

The Eco^2 assessment methodology uses Eco-indicator 99 methodology and cost-benefit analysis to assess the ecological and economical impacts associated with recycling activities in different end-of-life options for WEEE. In Eco-indicator 99 methodology (PRE Consultants 2000) which is a damage oriented LCA method, all environmental effects are translated to actual damage inflicted to eco-system quality, human health and resource depletion, and the final result is expressed in a single score (i.e. a point) that indicates the overall damage to the environment. A brief description of the Eco-indicator 99 method is included in *Appendix 3*. The results of the ecological and economical assessments are combined in the form of a combined Eco^2 ratio, which helps in identifying the most appropriate end-of-life options for treating WEEE.

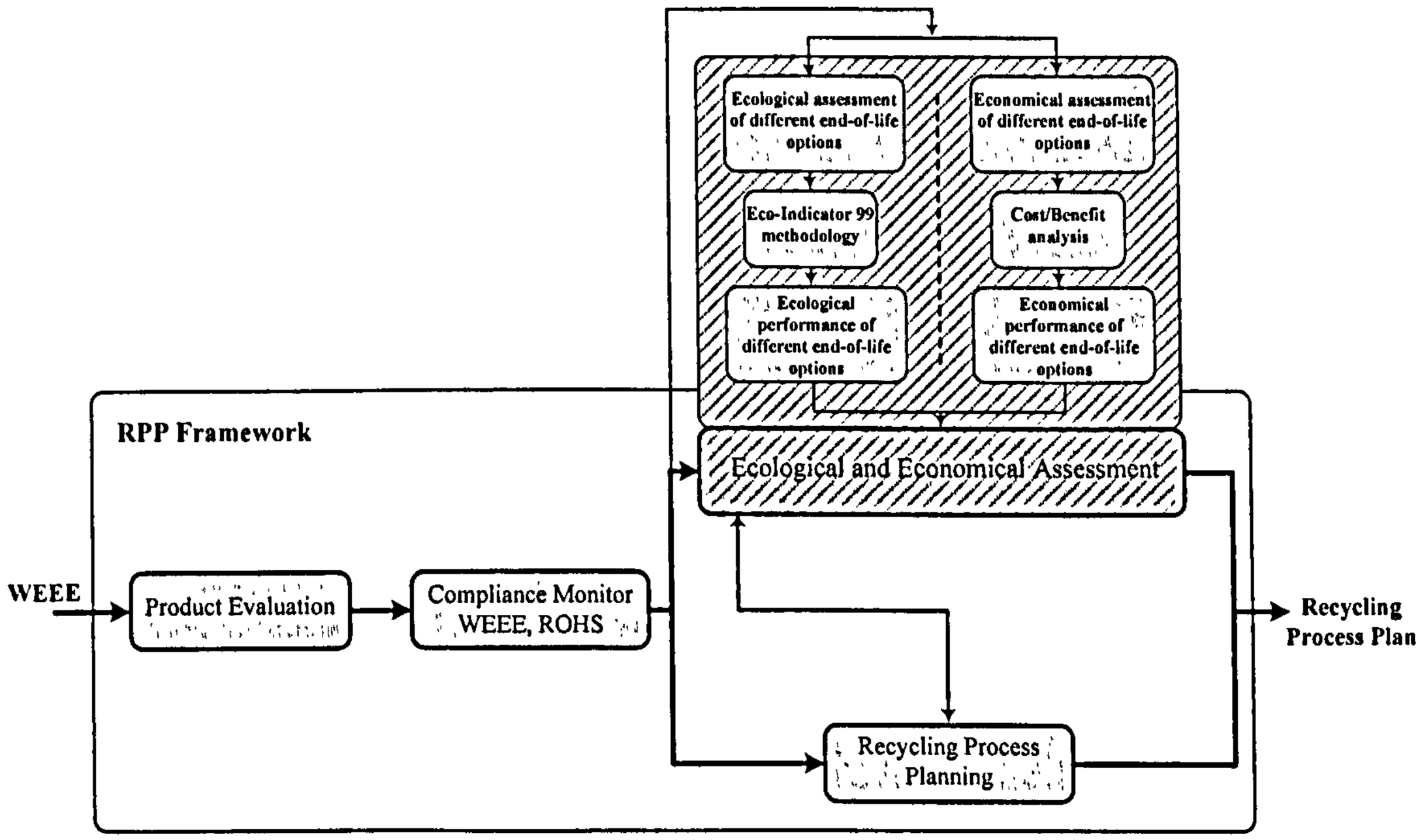


Figure 8.2: Application of Eco^2 assessment within the RPP framework

Figure 8.3 provides an overview of the various tasks involved in the Eco^2 assessment methodology. The decision support process in the Eco^2 assessment methodology starts with the identification of different end-of-life options available for used product under consideration. These end-of-life options are then assessed in terms of their ecological and economical performance through two parallel assessment stages. Finally, the results from these assessment stages are combined to generate combined Eco^2 ranking for different end-of-life options. Different tasks involved in the Eco^2 assessment methodology are described in more detail in the next section.

8.4 Tasks involved in the Eco^2 Assessment Methodology

The different tasks included in the Eco^2 methodology (see Figure 8.3) are listed below and are described in more detail in the remaining sections of this chapter.

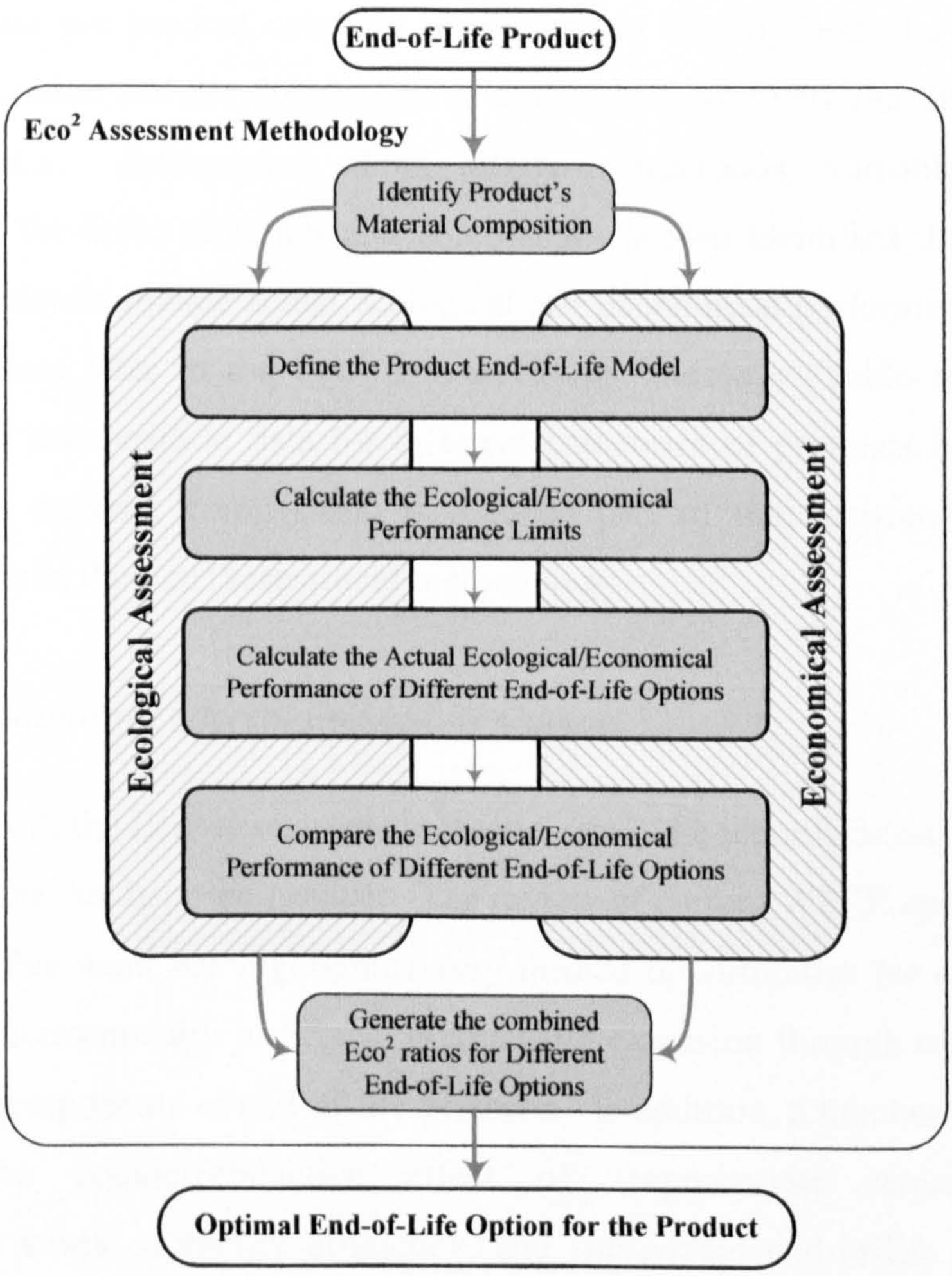


Figure 8.3: Tasks involved in the Eco^2 assessment methodology

i. Identification of product material composition
ii. Identification of different end-of-life options
iii. Calculation of the performance limits
iv. Calculation of the actual performance of different end-of-life options
v. Comparison of the performance of different end-of-life options
vi. Generation of the combined Eco^2 ratios for ranking different end-of-life options

8.4.1 Identification of Product's Material Composition

Both the ecological and economical assessment is based on the material composition of the end-of-life product. The required information about the composition of main materials like ferrous metals, non-ferrous metals, flame retardant plastics, non-flame retardant plastics, glass etc. in various categories of WEEE is identified through the product evaluation stage of the RPP framework (see section 7.4.1). The material composition data per product category is adjusted to identify both the actual product material composition and the distribution of materials shared between the relevant end-of-life treatments. Information about different hazardous, valuable and penalty (contaminating the hulk) materials and components is also identified through this task which helps to determine the actual ecological and economical performance of different end-of-life options later in the Eco^2 assessment methodology. Table 8.1 outlines the typical material composition data for different categories of products in WEEE. The information on material composition is used as part of the decision-making within subsequent tasks in the Eco^2 assessment methodology.

8.4.2 Identification of Different End-of-Life Options

The second task in the Eco^2 assessment methodology is the identification of feasible end-of-life options for the disposed product. The review of current WEEE applications in the UK as part of this work has highlighted very limited opportunities for environmentally beneficial and economically justifiable product life extension through remanufacture or reuse of parts/components of end-of-life products. In addition, a number of studies have highlighted the counterproductive effect of inappropriate remanufacture/reuse applications in terms of energy efficiency, and subsequent end-of-life and release of toxic substances (Rose *et al.* 1999; Rose 2000; Chalkley *et al.* 2003).

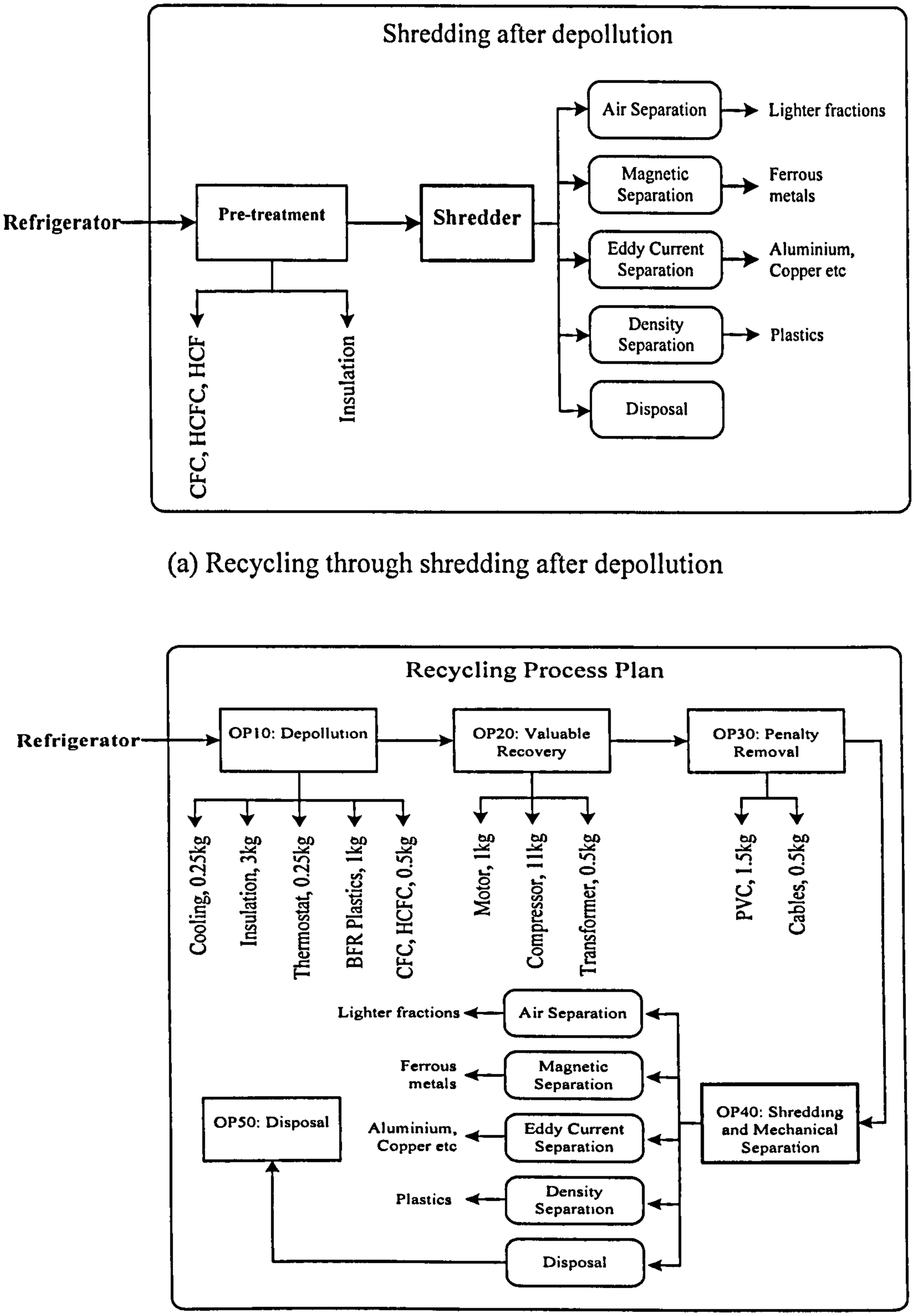
Material	Large Household Appliances (%)	Small Household Appliances (%)	IT & Telecom Equipment (%)	Consumer Equipment (%)
Iron and steel	47.9	20.4	45	20.8
Flame retarded plastics	5.3	21	20.6	12.5
Non-flame retarded plastics	15.3	25.1	11.4	15.8
Wood, plywood, paper etc.	2.6	1.3	1.3	1
Aluminium	4.7	6.5	1.7	2.4
Copper	7	3.4	2	3.5
Other metals	1	3	3.9	3
Glass	5.4	3.4	1.2	37
Rubber	1.1	0.9	0.5	0.7
Concrete and ceramics	2	1.3	0	0
Others	7	13.7	13.7	3.3

Table 8.1: Material composition of different categories of equipment in WEEE

It is acknowledged that remanufacturing has a strong case where original equipment manufacturers are actively involved and include the end-of-life management of their products in their business models (e.g. Xerox remanufacturing their photocopiers). However, remanufacturing is only justifiable where there is a strong market for remanufactured products and the cost of remanufacturing is insignificant as compared to the value of the new product. Hence, the complete reuse and remanufacture are not considered as feasible end-of-life options for WEEE recycling in the Eco^2 assessment methodology.

The Eco^2 methodology considers the most common existing end-of-life options for WEEE together with the recycling options included in the bespoke recycling process plan proposed by the research reported in this thesis. Currently, depollution has become an essential part of the EoL management, hence shredding of whole product without pre-treatment is also not considered as a feasible EoL option. Eco^2 assessment methodology considers the following three end-of-life options for further assessment.

- Recycling through Shredding after depollution (Figure 8.4a)
- Recycling through Recycling process plan (Figure 8.4b)
- Landfilling



(a) Recycling through shredding after depollution

(b) Recycling through recycling process plan

Figure 8.4: Schematic of different end-of-life options for a typical electrical and electronic equipment

Currently recycling practices mainly involve the shredding process to breaking the product down into small pieces to facilitate the separation of different materials. Recycling process plan option involves utilising a combination of different end-of-life options for individual components and materials contained within the product, and consists of a number of bespoke recovery and recycling processes for each product type being recycled.

8.4.3 Calculation of the Performance Limits

The performance limits are calculated to provide a scale for the evaluation and assessment of the actual ecological and economical performance of different end-of-life options available for product recycling. The upper limit of ecological and economical performance is based on the assumption that all materials contained in the product are completely recovered and recycled (zero landfilling). Obviously, this best case scenario is practically not achievable and its theoretical value serves merely as a fixed (upper) point in the evaluation scale, representing a Best Case Scenario (BCS). Equations (8.1) and (8.2) are used to calculate the upper limit of ecological and economical performance respectively.

$$BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) \tag{8.1}$$

$$BCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{BCS}) \tag{8.2}$$

Where

BCS_{ecol} is the upper limit (Best Case Scenario) of ecological performance *(mPt)*;

BCS_{econ} is the upper limit (Best Case Scenario) of economical performance *(£)*;

m_i is the mass of material i in the product *(kg)*;

EIi_{BCS} is the ecological impact of material i in the best case scenario *(mPt/kg)*;

CIi_{BCS} is the material revenue of material i in the best case scenario *(£/kg)*.

Equation (8.1) describes the ecological benefit (gain) associated with the recycling and subsequent reuse of all materials in a product. This ecological gain represents the ecological impact value of primary virgin material extraction that is actually substituted

by recycled material and must therefore not be extracted. It should be noted that in the Eco-indicator 99 methodology a positive ecological impact (+mPt) indicates an environmental burden, whereas a negative value (-mPt) refers to an avoided environmental burden, which is known as an environmental gain. In a similar way, Equation (8.2) describes the economical gain through the material revenues of all materials in the product. The actual prices for various scrap metal are taken into consideration in order to calculate the material revenues associated with different material streams.

The lower limit of ecological and economical performance is based on the assumption that all materials contained in the product are being sent to landfill. It should be noted that in the worst case scenario of sending the complete product to landfill, the cost of depollution is also added. Equations (8.3) and (8.4) are used to calculate the lower limit, representing a Worst Case Scenario (WCS), of ecological and economical performance respectively.

$$WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) \tag{8.3}$$

$$WCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{WCS}) \tag{8.4}$$

Where

WCS_{ecol}	is the lower limit (Worst Case Scenario) of ecological performance *(mPt)*;
WCS_{econ}	is the lower limit (Worst Case Scenario) of economical performance *(£)*;
m_i	is the mass of material i in the product *(kg)*;
EIi_{WCS}	is the ecological impact value of material i in the worst case scenario *(mPt/kg)*;
CIi_{WCS}	is the material revenue value of material i in the worst case scenario *(£/kg)*.

Equation (8.3) and (8.4) describe the ecological and economical impacts associated with landfilling all materials in the product. The eco-indicator value for the ecological impact of sending the material *i* to landfill 'EIi_{WCS}' (usually a + mPt value) and related actual cost of sending this material to landfill 'CIi_{WCS}' (usually a +£ cost) are used to calculate the related ecological and economical impacts.

8.4.4 Calculation of the Actual Performance of Different End-of-Life Options

The actual ecological and economical performances of different end-of-life options are calculated once the upper and lower performance limits are defined. The actual ecological performance (AP_{ecol}) of a specific end-of-life option of a product under consideration is calculated by Equation (8.5). Provisions are made for the material degradations and process inefficiencies to be considered while calculating the actual ecological performance associated with different end-of-life options.

In a similar manner, the actual economical performance (AP_{econ}) of a certain end-of-life option of a product under consideration is calculated by Equation (8.6). A parametric cost-benefit analysis approach is used to calculate the actual economical performance of different end-of-life options of a product under consideration. All respective end-of-life processes are quantified according to the different costs, e.g. disassembly cost, processing cost, disposal cost, and material revenues. The actual economical performance is then calculated by summing up all the relevant costs and revenues associated with different recovery and recycling activities for a specific end-of-life option.

$$AP_{ecol} = \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) \tag{8.5}$$

$$AP_{econ} = \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) \tag{8.6}$$

Where

AP_{ecol} is the actual ecological performance of a certain end-of-life option *(mPt)*;

AP_{econ} is the actual economical performance of a certain end-of-life option *(£)*;

m_i is the mass of material i in the product *(kg)*;

PE_i is the efficiency of the separation process used for material i;

EIi_{AP} is the ecological impact of material i in a certain end-of-life route *(mPt/kg)*;

CIi_{AP} is the cost impact of material i in a certain end-of-life route *(£/kg)*;

G_i is the grade in which material i is recovered.

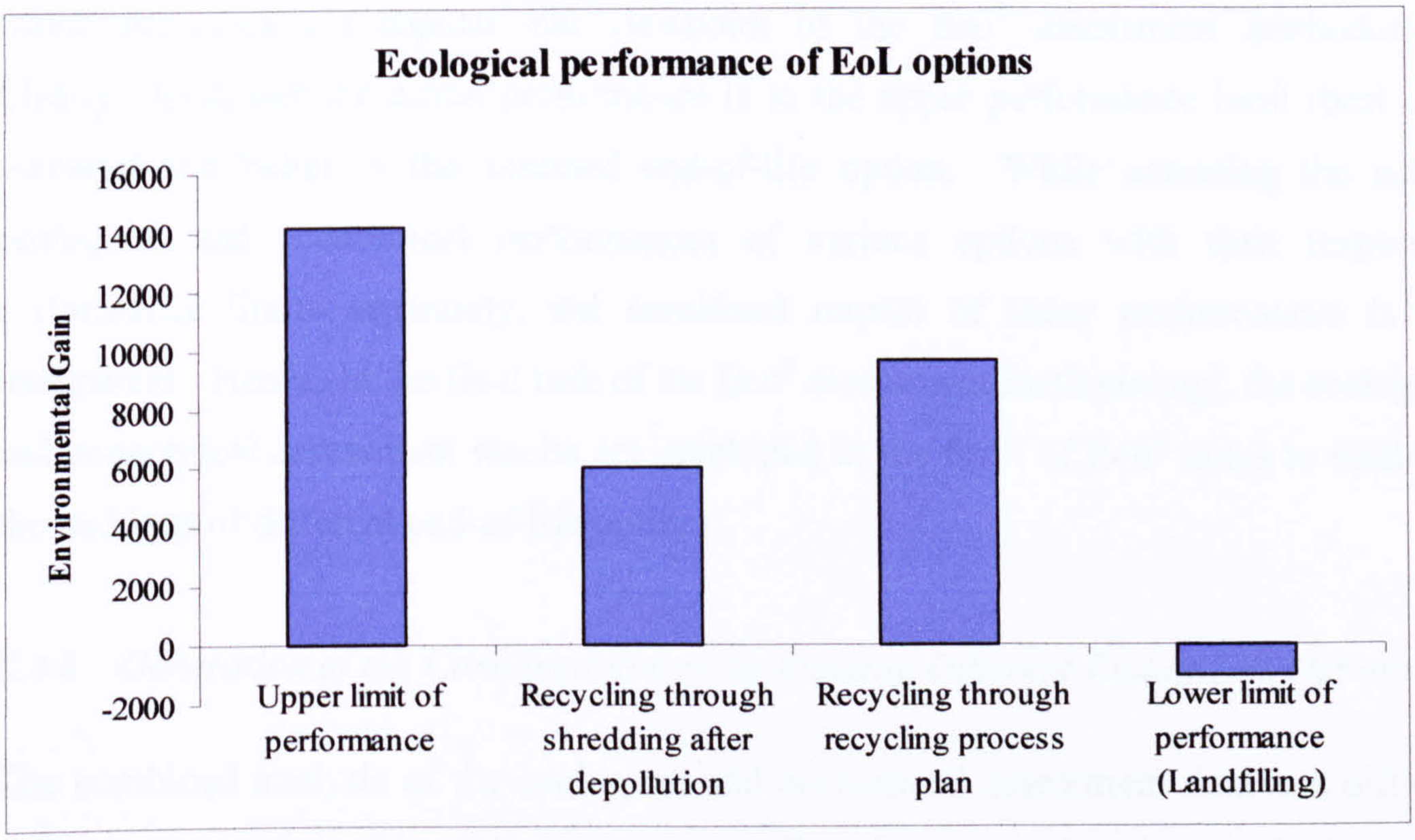
It must be noted that the scope of the Eco^2 assessment only covers the activities taking place within a particular recycling facility, and the ecological and economical performance of activities related to collection, transportation, storage of WEEE and subsequent secondary material production processes are not considered. Table 8.2 lists other assumptions made in this research regarding the calculation of the ecological and economical performances of WEEE recycling.

8.4.5 Comparison of the Performance of Different End-of-Life Options

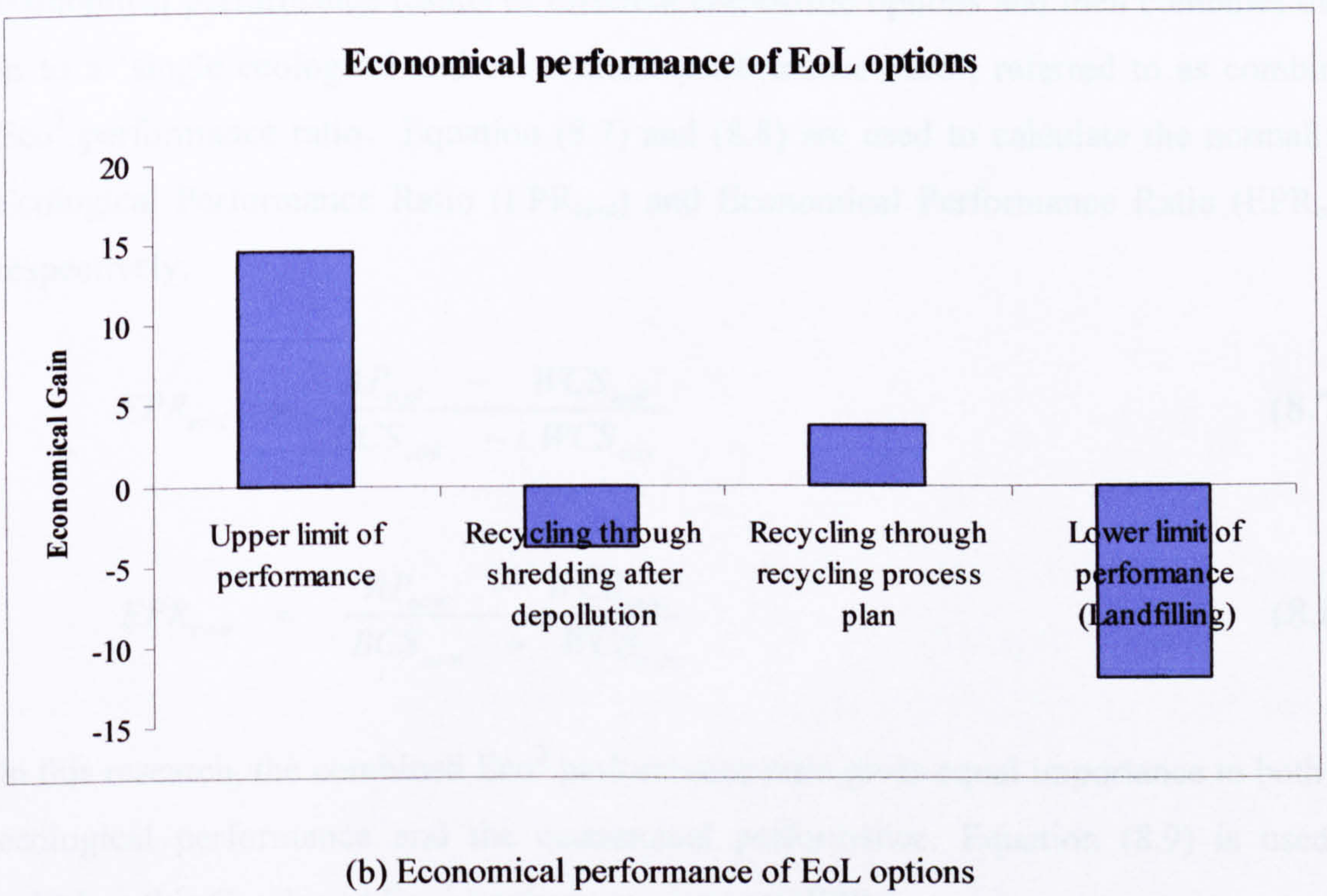
Once the actual ecological and economical performances associated with different end-of-life options for a certain product are calculated, they are evaluated in conjunction with the respective upper and lower limits of the ecological and economical performance. Figure 8.5 illustrates this comparison process by drawing the sample ecological and economical performances of different end-of-life options for a specific product with the respective performance limits.

Assumption	Comments
Scope of the Eco^2 assessment methodology	Activities involved in transforming the used product at a recycling facility into individual materials, parts and assemblies for further treatment.
Product level of detail	It is the requirement for the application of Eco^2 assessment methodology that the main materials in the product (ferrous metals, non-ferrous metals, plastics, glass etc.) and their distribution over the relevant end-of-life routes are known.
Material composition of the product, its parts and subassemblies	Material composition data for a specific product is derived from the generic material composition data of WEEE category in which the product falls. Sensible assumptions are made to identify the material composition of parts and subassemblies.
Material degradation and process efficiencies	Data regarding material degradation and process efficiencies associated with different recovery and recycling processes is adapted from (Coates 2007) to be used for Eco^2 assessment.

Table 8.2: Basic assumptions about the calculation of Eco^2 performances



(a) Ecological performance of EoL options



(b) Economical performance of EoL options

Figure 8.5: A sample comparison diagram for performances of different EoL options

An example of an actual comparison diagram for a refrigerator is given in chapter 9 which describes a computational viewpoint of the Eco^2 assessment methodology. Clearly, the closer the actual performance is to the upper performance limit (best case scenario) the better is the assessed end-of-life option. While assessing the actual ecological and economical performances of various options with their respective performance limits separately, the combined impact of these performances is not transparent. Hence, in the final task of the Eco^2 assessment methodology, the ecological and economical assessment results are combined in the form of Eco^2 ratios to establish the rankings of different end-of-life options.

8.4.6 Generation of the Combined Ratios for Ranking Different End-of-Life Options

The combined analysis of the ecological and economical assessment data is a difficult but necessary task to gain an insight into overall performance of each end-of-life option. This research has adopted a data analysis method which normalises the ecological and economical performance results of different end-of-life options and then combines them in to a 'single ecological and economical performance ratio', referred to as combined Eco^2 performance ratio. Equation (8.7) and (8.8) are used to calculate the normalised Ecological Performance Ratio (EPR_{ecol}) and Economical Performance Ratio (EPR_{econ}) respectively.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} \quad \textbf{(8.7)}$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} \quad \textbf{(8.8)}$$

In this research, the combined Eco^2 performance ratio gives equal importance to both the ecological performance and the economical performance. Equation (8.9) is used to calculate this Combined Eco^2 Performance Ratio (C*E*PR).

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} \quad \textbf{(8.9)}$$

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for the upper performance limit. It should be noted that in this case upper performance limit will become actual performance (i.e. $AP_{ecol} = BCS_{ecol}$ and $AP_{econ} = BCS_{econ}$), and therefore:

$$EPR_{ecol} = \frac{BCS_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = 1$$

$$EPR_{econ} = \frac{BCS_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = 1$$

Similarly, Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for the lower performance limit. It should be noted that in this case lower performance limit will become actual performance (i.e. $AP_{ecol} = WCS_{ecol}$ and $AP_{econ} = WCS_{econ}$).

$$EPR_{ecol} = \frac{WCS_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = 0$$

$$EPR_{econ} = \frac{WCS_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = 0$$

It is clear from the above calculations that C*E*PR ranges from '0' to '1', with '0' being the lower performance limit (worst case scenario) and '1' being the upper performance limit (best case scenario). Higher value of C*E*PR (close to 1) represents a good overall performance of the assessed end-of-life option. Similarly, lower value of C*E*PR (close to 0) represents a bad overall performance of the assessed end-of-life option.

Finally, the combined Eco^2 performance ratios are plotted on a bar chart to establish the overall ranking of different end-of-life options and to identify the best end-of-life option for the product under consideration. A number of case studies are presented in chapter 10 to illustrate the computational viewpoint of the proposed Eco^2 assessment methodology to identify the best end-of-life options for chosen products.

8.5 Chapter Summary

This chapter has described the novel Eco^2 assessment methodology developed in this research in order to compare the ecological and economical performance of various end-of-life options and provides decision support in selecting the most appropriate end-of-life option available for a specific product. A number of alternative methods like life cycle assessment, life cycle costing and ABC costing were initially tried in this research to calculate the related ecological and economical impacts associated with WEEE recycling. These methods tend to be too complex and require a significantly long time to generate the results, and are not practical to be used to support the decisions involved in the end-of-life management of WEEE. Eco-efficiency charts were also tried by this research to calculate the combined (ecological and economical) performances of different end-of-life options, but a number of shortcomings related to ranking the combined performances of different EoL options were identified.

This research has developed a novel method which is simple and at the same time effective to calculate the ecological and economical performances of different EoL options for WEEE recycling. Furthermore, the normalising scales and combined analysis of ecological and economical performances as performance ratios developed by this research is clearly a contribution to the existing field of knowledge in this area. Different tasks involved in the assessment methodology as well as their theoretical background are detailed in the various sections of this chapter. The application of various stages of the recycling process planning framework including the ecological and economical assessment of various end-of-life options involve significant amount of data processing and calculations, and therefore, a computational viewpoint of the RPP framework and Eco^2 assessment has been developed which will be described in chapter 9.

Chapter 9

A Computer Aided Recycling Process Planner

9.1 Introduction

The previous two chapters have discussed the various tasks involved in the different stages of the RPP framework. This chapter describes the integration of all these stages and tasks involved in them into one homogenised system, to assist in the generation of the bespoke recycling process plans for electrical and electronic products. The implementation of the various aspects of the RPP framework through different modules of the computer aided recycling process planner is intended to be a portal for the creation of bespoke, quick, and consistent eco-efficient recycling process plans for WEEE. The application of this process planner will be further demonstrated within chapter 10 through a number of case studies.

9.2 A Computational Viewpoint of the Recycling Process Planner

The research assertion within this thesis proposed a systematic approach to recycling process planning, together with an end-of-life decision support mechanism for assessing the ecological and economical impacts of recycling activities, can improve the end-of-life performance and legislative compliance of WEEE recovery sector. However, the generation of eco-efficient recycling routes for WEEE is a complex problem. It involves concurrent consideration of product and process related end-of-life issues. Therefore, to support the implementation of the RPP framework, a prototype Computer Aided Recycling Process Planner (CA*R*PP) has been developed in this research. Different stages of the RPP framework are supported through various modules of the CA*R*PP, which are implemented using a combination of Visual Basic, Microsoft Access, and Microsoft Excel. Figure 9.1 provides an overview of the implementation of the various stages of the RPP framework through the CA*R*PP. The significant advantage of using a computer aided recycling process planning approach as opposed to a manual recycling process planning approach is that the different requirements for effective end-of-life management including consistency in recycling practices, availability of product

recycling data, and information about targeted materials and components in WEEE could be addressed. The remaining sections of this chapter describe the implementation of the RPP framework through different modules of the CA*R*PP.

9.3 Computer Aided Recycling Process Planner

The generation of bespoke eco-efficient recycling process plans for WEEE involves a significant amount of data processing and decision making tasks. Therefore, a Computer aided Recycling Process Planner is developed which consists of four modules, namely a user interface module, a database module, a recycling process planning module and an assessment module as depicted in Figure 9.2. Initial concepts related to CA*R*PP are reported in Bakar and Rahimifard (2007a) (see *Appendix 4*). Different modules of the CA*R*PP and their relation to the RPP framework stages are briefly outlined below and are described in more detail in the remaining sections of this chapter.

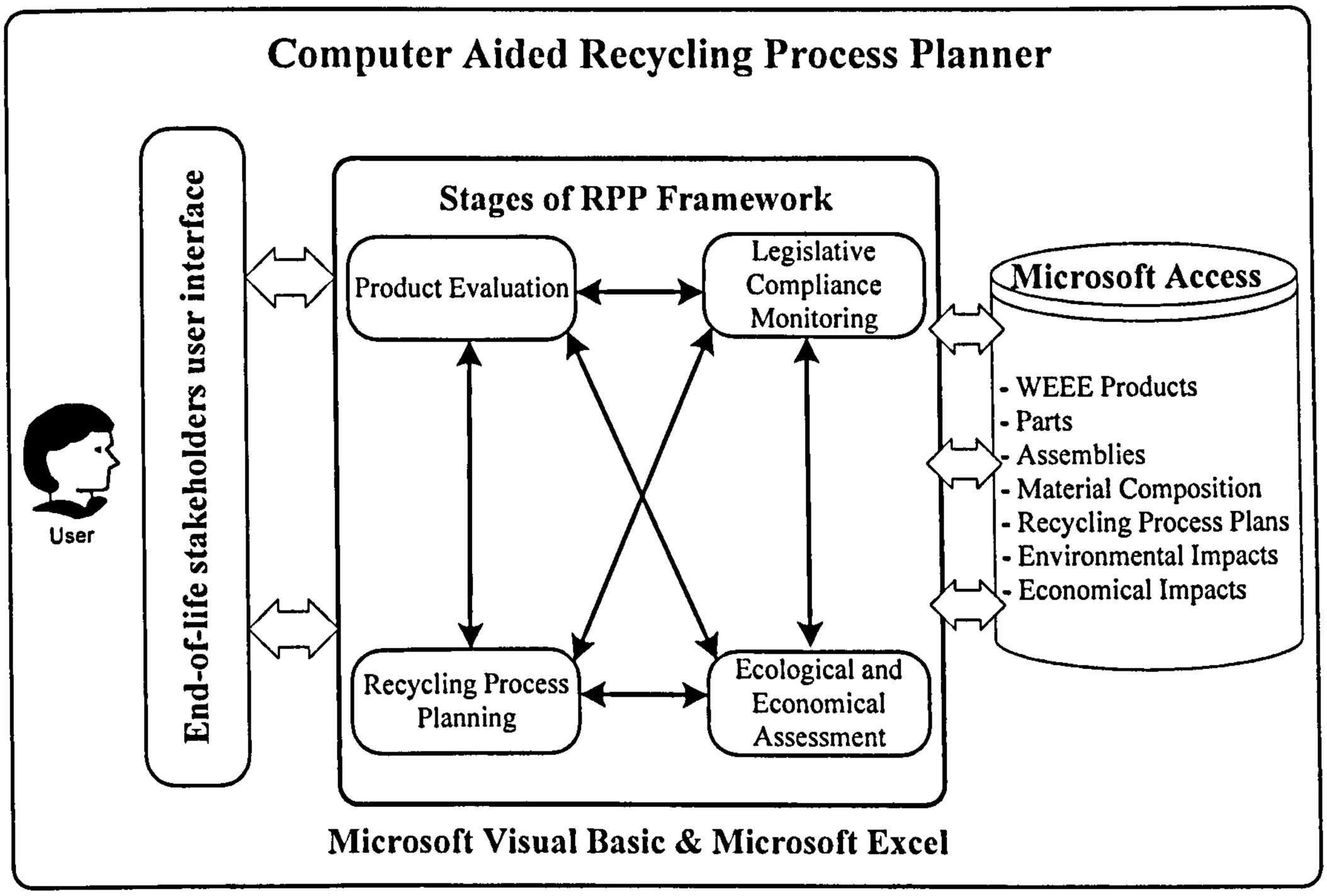


Figure 9.1: Overview of the RPP framework implementation through the CA*R*PP

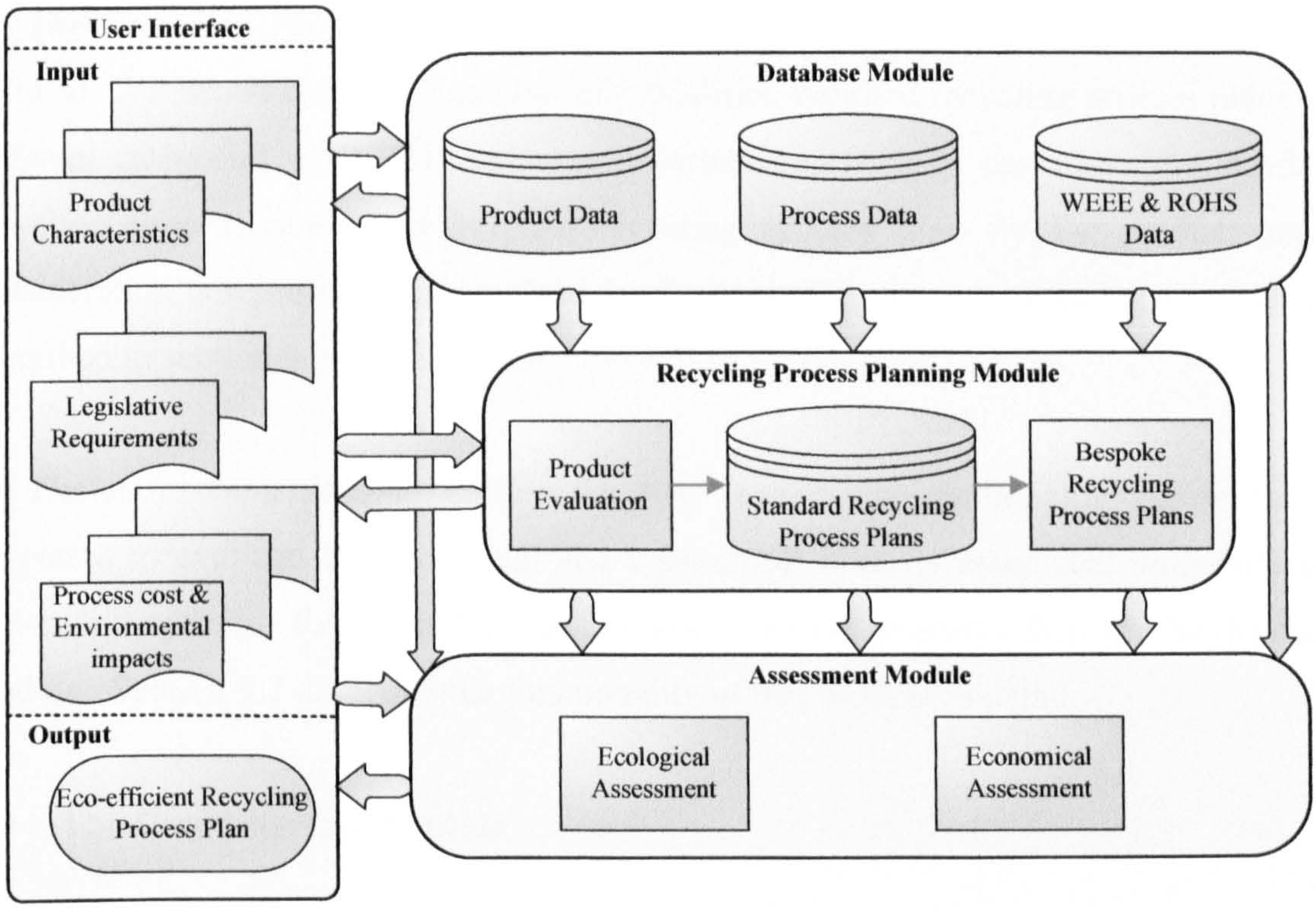


Figure 9.2: Architecture of the CA***R***PP

i) The User Interface Module provides a systematic process for the implementation of the 'product evaluation' stage of the RPP framework described in section 7.4.1. The interface has been developed in Microsoft Visual Basic 6 and is integrated with Microsoft Access to facilitate the related data retrieval and storage. The user interface module contains a number of tasks to identify the product characteristics and legislative requirements which are later used in the recycling process planning module. These tasks are further detailed in section 9.4.

ii) The Database Module facilitates the data storage and retrieval tasks within the CA***R***PP. It contains the product, process and legislative data which is used to generate the recycling process plans for WEEE, and supports the ecological and economical assessment. The legislative compliance monitoring stage of the RPP framework is implemented through this module, utilising the detailed information included in the European Commission report outlining the specifics of WEEE and RoHS Directives. The database module is described further in section 9.5.

iii) The Recycling Process Planning Module generates the bespoke recycling process plans for WEEE. It contains a number of predefined standard recycling process plans for different categories of WEEE and uses a variant approach to customise the standard recycling process plans into bespoke recycling process plan for the product under consideration. Various tasks involved in the recycling process planning module are described in section 9.6.

iv) The Assessment Module utilises the Eco^2 assessment methodology presented in chapter 8 to evaluate the ecological and economical impacts associated with different end-of-life options. Required data for this assessment is available through the database module. Section 9.7 describes the functionality of this module in detail.

9.4 The User Interface Module

The user interface module receives and controls the user input and gives access to the CA*R*PP output. The main menu of the user interface module of the CA*R*PP, which is shown in Figure 9.3, is split into three parts, the generation of a new recycling process plan, the environmental assessment of a recycling process plan, and the economical assessment of a recycling process plan. The generation of a new recycling process plan conducts the product evaluation, which collects information used by other modules of the CA*R*PP in order to generate bespoke recycling process plans along with the ecological and economical impact assessment. The other two parts of the main menu bypass the product evaluation and provide the access to an existing bespoke recycling process plan, which can then be assessed through the assessment module in order to calculate the ecological and economical impacts. The product evaluation process guides the user through different tasks to collect information on the product, its WEEE category and material composition as well as hazardous materials and components, valuable materials and components, penalty materials and components included in the product.

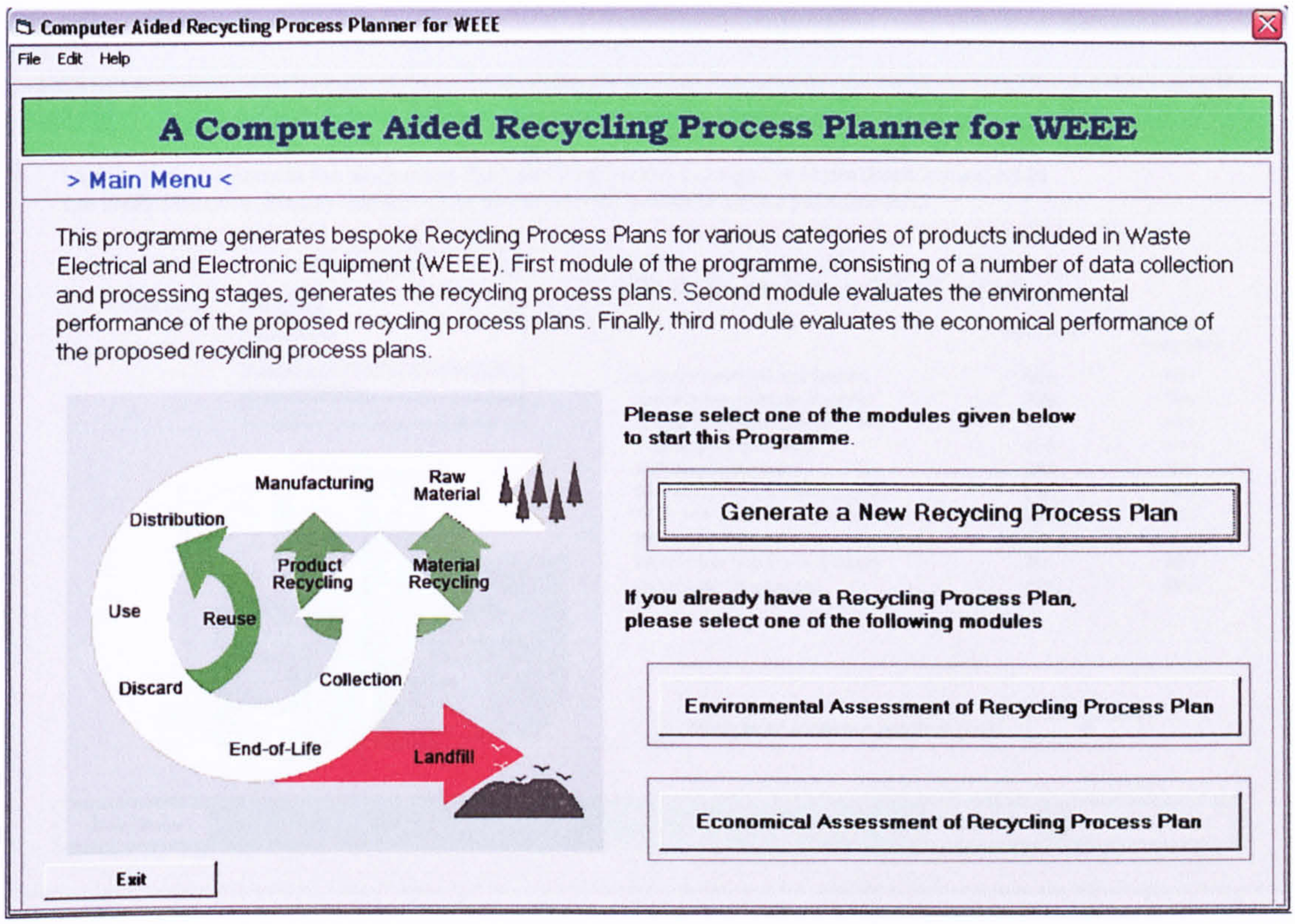


Figure 9.3: Main menu of the CA***R***PP

The evaluation process starts by identifying the product category according to the WEEE directive to establish the legislative requirements for the product, as shown in Figure 9.4. An indicative weight is assigned to the product which can then be used to calculate the recovery and recycling targets for the product. Once a product is selected, the user is then asked to confirm the hazardous and toxic substances present in the product (see Figure 9.5). These identified hazardous and toxic substances trigger the appropriate pre-treatment processes to be included in the product's bespoke recycling process plan (see Figure 9.13). The pre-treatment is essential in order to comply with the legislative requirements related to the treatment of hazardous materials. Similarly, the third evaluation task within the user interface module identifies the valuable materials and components present in the product as shown in Figure 9.6.

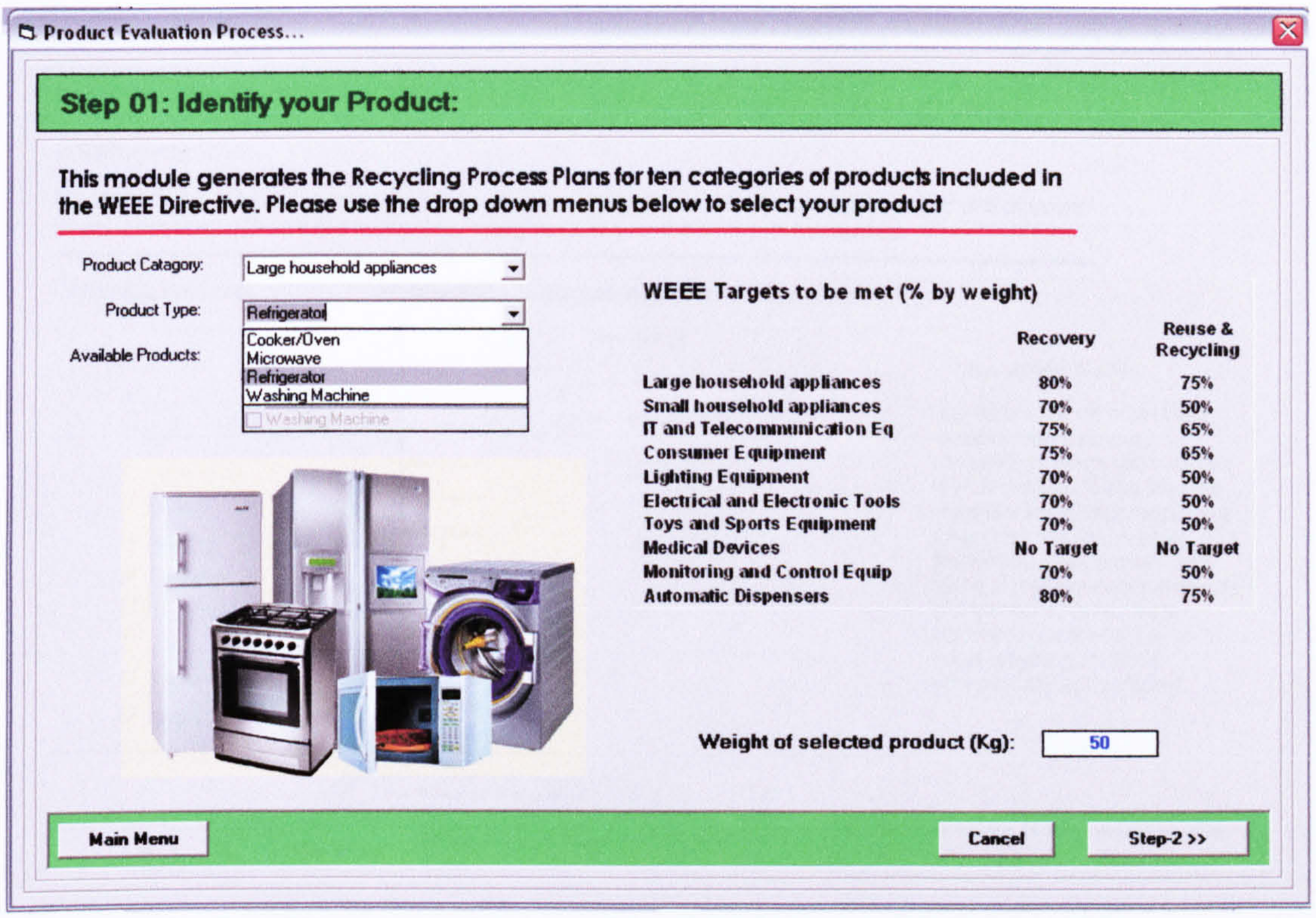


Figure 9.4: Identification of the product

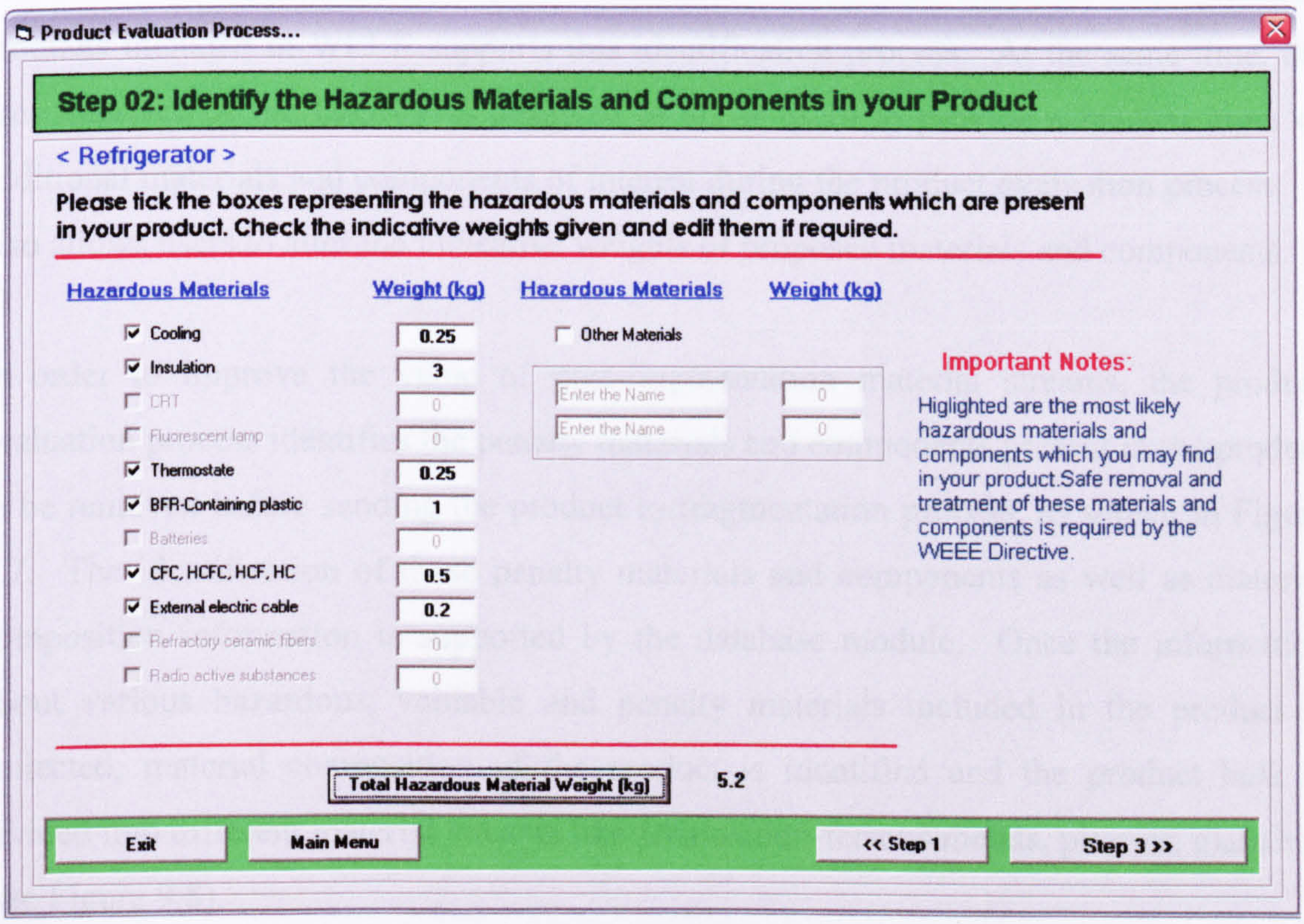


Figure 9.5: Identification of the hazardous materials and components in the product

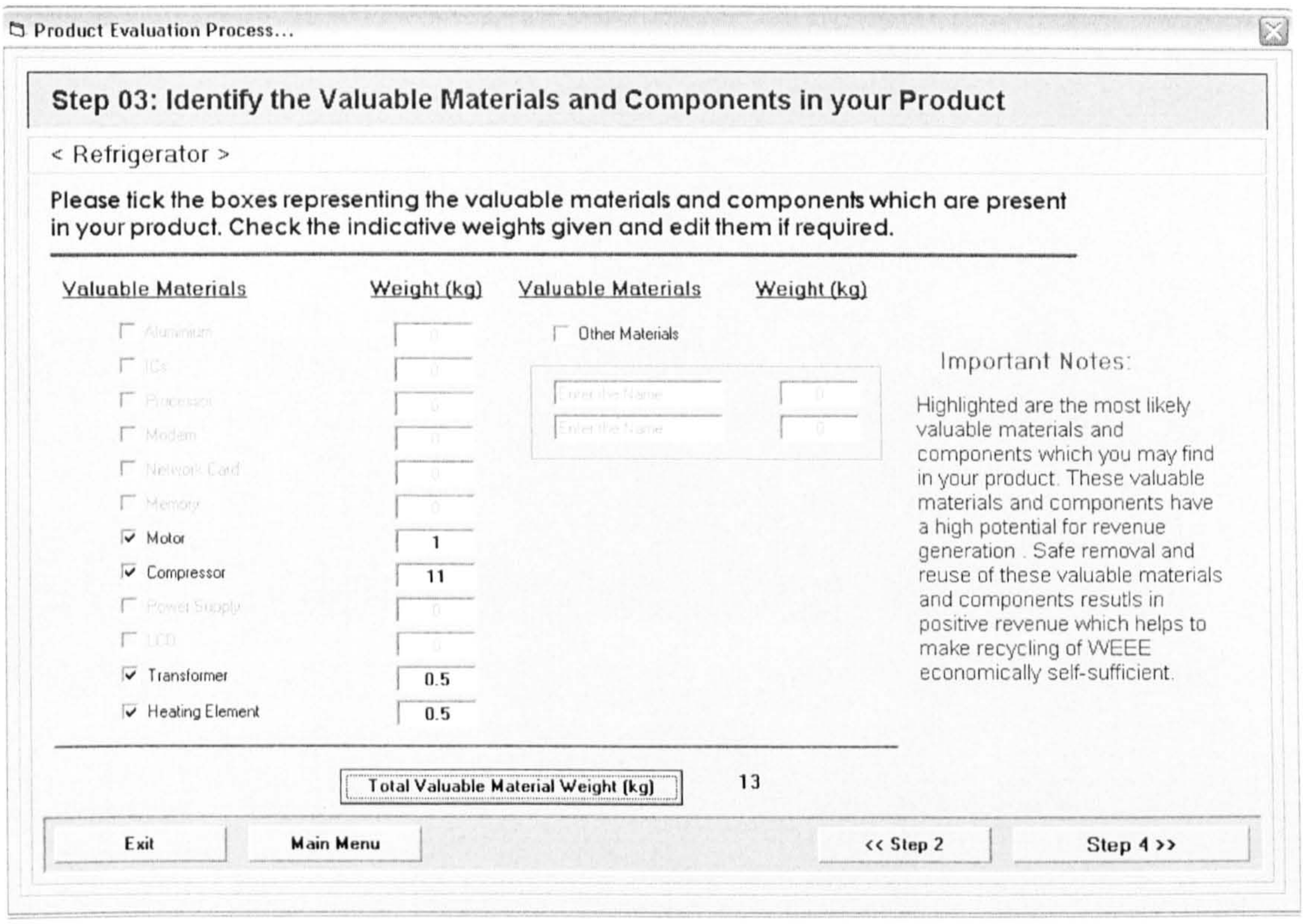


Figure 9.6: Identification of the valuable materials and components in the product

An extensive database containing information about different electrical and electronic products included in WEEE supports this identification process. At the same time, the user interface of the CA***R***PP is designed to allow users to provide a manual input of additional materials and components of interest during the product evaluation process. It also allows users to alter the indicative weights of proposed materials and components.

In order to improve the value of post-fragmentation material streams, the product evaluation process identifies the penalty materials and components present in the product to be removed before sending the product to fragmentation process, as shown in Figure 9.7. The identification of these penalty materials and components as well as material composition information is supported by the database module. Once the information about various hazardous, valuable and penalty materials included in the product is collected; material composition of the product is identified and the product hulk is divided into different material streams like ferrous/non-ferrous metals, plastics, glass etc. (see Figure 9.8).

Product Evaluation Process...

Step 04: Identify the Penalty Materials and Components in your Product

< Refrigerator >

Please tick the boxes representing the penalty materials and components which are present in your product. Check the indicative weights given and edit them if required.

Penalty Materials	Weight (kg)	Penalty Materials	Weight (kg)
Concrete	0	Other Materials	
Textile	0	Enter the Name	0
Wood	0	Enter the Name	0
☑ PVC	1.5		
Carpet	0		
☑ Cables	0.25		

Important Notes:

Highlighted are the most likely penalty materials and componenets which you may find in your product . These penalty materials and components causes serious problems for post-fragmentation material separation. Removing these penalty materials and components before the product hulk is sent to the shredder is a value-added activity which eliminates the contaminations in shredded material streams.

Total Penalty Material Weight (kg) 1.75

Exit | Main Menu | << Step 3 | Step 5 >>

Figure 9.7: Identification of the penalty materials and components in the product

Product Evaluation Process ...

Step 05: Shredding and Material Separation for your Product

< Refrigerator >

>> Weight of product before shredding (Kg): 30.05

Based on the generic material composition of WEEE the weight of each material type included in your product is calculated below. Check the weights below and edit them if required.

Each material stream is linked to an appropriate material separation process. Separability efficiency of each material separation process is considered before calculating the total material recovered from the product.

Material Type	Composition (weight %)	Weight (kg)	Process Type	Separatability Efficiency	Material Processed	Material Recovered
☑ Iron and steel	47.9	14.39	Managatic Separation	0.98	14.39	14.10
☑ Flame retarded plastics	5.3	1.592	Skin Floatation	0.70	1.592	1.114
☑ Non-Flame retarded plastics	15.3	4.597	Electrostatic Separation	0.65	4.597	2.988
☑ Wood and plywood	2.6	0.781	Air Separation	0.85	0.781	0.663
☑ Aluminium	4.7	1.412				
☑ Copper	7	2.103	Eddy Current Separation	0.9	3.815	3.433
☑ Other Metals	1	0.300				
☑ Glass	5.4	1.622				
☑ Rubber	1.1	0.330	Heavy Medium Separation	0.75	4.866	3.649
☑ Concret and ceramics	2	0.601				
☑ Others	7.7	2.313				

Recalculate | Total Material Recovered: 25.94

Exit | Main Menu | << Step 4 | Step 6 >>

Figure 9.8: Identification of the material composition and mechanical separation

This material mix information is used to identify the appropriate post-fragmentation recycling processes for the product under consideration. The screenshot in Figure 9.8 displays the distribution of various material streams within the product hulk. This distribution is based on the generic composition of WEEE (Taberman *et al.* 1995) and the user can adjust this composition data to suit a specific product. Different parameters of post-fragmentation material streams (e.g. shape, size, density, conductivity, etc.) are used to distinguish a target material from the rest of the material stream in separation processes. The efficiencies of the separation processes, referred to as seperatability efficiencies (see Figure 9.8), considered in the CA*R*PP are based on previous research which investigated the impacts of the various material streams versus separation process efficiencies (Coates 2007). It is envisaged that more accurate industrial data relating to efficiencies of the separation processes can improve the accuracy of the CA*R*PP.

The final task in the product evaluation identifies the safe disposal processes to be used for the product under consideration, as shown in Figure 9.9. At present, due to inefficiencies of the mechanical separation processes and economic concerns over the available recycling technologies, a percentage of the post-fragmented material referred to as shredder residue cannot be reused or recycled and needs to be safely disposed through incineration or landfill.

9.5 The Database Module

The database module stores a variety of different end-of-life information (e.g. product data, process data and legislative requirements data) and provides access to this information to other modules in the CA*R*PP. The user interface module is supported by this database module throughout the product evaluation in order to facilitate the data entry. Furthermore, any new product information obtained during product evaluation is also added to the respective database within the database module.

The product database contains information about product characteristics, its WEEE category, weight, material composition, and components. Figure 9.10 depicts a product data table listing different hazardous, valuable and penalty materials found in typical electrical and electronic equipment together with their indicative weights as percentage of the total product weight.

Product Evaluation Process ...

Step 06: Identify Safe Disposal for your Product

< Refrigerator >

Inefficiencies of the material separation processes and economics of available recycling technologies necessitate safe disposal of the shredder residue. Certain hazardous substances removed from WEEE also require safe disposal.

Weight of the Product to be disposed (kg) 4.11

Disposal suitable for landfill	Weight (kg)
☑ Controlled landfill of Skin floatation process waste	0.350
☑ Dispose the waste as MWS	0.220

Disposal suitable for Incineration	
☑ Controlled Incineration of Electrostatic seperation waste	1.195
☑ Incinerate Air separation process fluff	0.085
☑ Incinerate Heavy medium separation process fluff	0.778
☑ Controlled incincration of other hazardous materials	0

Important Notes:

Incineration of WEEE can result in high concentration of metals, heavy metals in the slag, the flue gas or the filter cakes. Care is to be taken to dispose certain materials included in the WEEE which are not suitable for incineration in view of the hazardous nature of the flue gas residues and are better to be sent to controlled landfill.

Exit | Main Menu | << Step 5 | Generate Recycling Process Plan

Figure 9.9: Identification of the safe disposal processes

Microsoft Access

File Edit View Insert Format Records Tools Window Help — Type a question for help

dssdata : Database (Access 2000 file format)

Product-compdata : Table

Chk	Mat/Comp	Refrigerator	Washing Machine	Toaster	Computer	Television	M
1	Cooling	0.005					
2	Insulation	0.06					
3	CRT					0.6	
4	Fluorescent lamp						
5	Thermostat	0.005	0.004	0.01			
6	BFR containing plastics	0.02	0.01	0.15	0.07	0.08	0.0
7	Batteries				0.001		
8	CFC, HCFC, HCF, HC	0.01					
9	External electrical cable	0.004	0.04	0.01	0.005	0.004	0.0
10	Refractory ceramic fibres						
11	Radio active substances						
13	Other Materials						
---	---	---	---	---	---	---	---
1	Aluminium						
2	ICs				0.03	0.02	
3	Processor				0.01		
4	Modem				0.012		
5	Network card				0.01		
6	Memory				0.006		0.0
7	Motor	0.02	0.20				
8	Compressor	0.22					
0	Power Supply						

Record: 20 of 83

Datasheet View — NUM

Figure 9.10: A product data table within the database module

The process database consists of a list of all contemporary recycling processes used in WEEE recycling and their associated environmental and economical impacts. These include the environmental impacts for material recycling, incineration and landfill as well as dismantling times and costs, processing costs, disposal costs and material revenues. Figure 9.11 depicts a process data table listing different recovery and recycling processes for WEEE along with their ecological and economical impacts in different end-of-life options.

The legislation database contains information about WEEE and RoHS directives and includes recovery targets, recycling targets and pre-treatment requirements (see Figure 9.12). As WEEE directive requires different recovery and recycling targets as well as pre-treatment requirements to be met across different categories of electrical and electronic equipment, the legislation database highlights the appropriate legislative requirements to be met by the recycling process planning module in identifying the appropriate recovery and recycling targets as well as pre-treatment requirements for the product under consideration.

Microsoft Access

File Edit View Insert Format Records Tools Window Help — Type a question for help

dssdata : Database (Access 2000 file format)

Process-data : Table

	Processdes		Material S	Landfill	Incineratic	Actual	Disass_	Proc_cos	Disposal	Mat_Rev	grade
	Sub-Op101	Remove Cooling for controlled Incineration	-160	16	46	46	0 7	-	0 025	-	1
	Sub-Op102	Remove Insulation for controlled Incineration	-480	8	2 8	2 8	1 6	-	0 025	-	1
	Sub-Op103	Remove CRT for further treatment	-83 5	1 935	-7.28	-83 5	5	0 015	-	0 0675	0 7
	Sub-Op104	Remove Fluorescent lamp for controlled Incin	-	-	-	-	-	-	-	-	-
	Sub-Op105	Remove Thermostate for Material Recovery	-363 6	1 4	-63 2	-363 6	0 9	0 015	-	0 362	0 85
	Sub-Op106	Remove BFR-Containing plastic for Material F	-360	1 4	-5 3	-360	1 8	0 015	-	0 2	0 7
	Sub-Op107	Remove Battenes for further treatment	-	-	-	-	-	-	-	-	-
	Sub-Op108	Remove CFC, HCFC, HCF, HC for controlled	-240	24	-36	-36	2 9	-	0 025	-	1
	Sub-Op109	Remove External electric cable for Material R	-1079	2.14	-82 7	-1079	0 1	0 015	-	1 1	0 75
	Sub-Op110	Remove Refractory ceramic fibre for further tr	-	-	-	-	-	-	-	-	-
	Sub-Op111	Remove Other Materials	-395 1	7 83	-20 7	-20.7	1	-	0 025	-	1
	Sub-Op201	Remove Aluminium for Material Recovery	-780	1 4	-110	-780	1 5	0 015	-	-	0 8
	Sub-Op202	Remove ICs for further treatment	-514 4	1 4	-	-514 4	0 9	0 015	-	0 6	0 65
	Sub-Op203	Remove Processor for further treatment	-514 4	1.4	-	-514 4	0.7	0 015	-	0 6	0.7
	Sub-Op204	Remove Modem for reuse	-282 4	2 21	-	-282 4	1	0 015	-	0 348	0.75
	Sub-Op205	Remove Network Card for further treatment	-767	2 96	-	-767	1.2	0 015	-	0.421	0.75
	Sub-Op206	Remove Memory for reuse	-466	2.24	-	-466	0 6	0 015	-	0 68	0 75
	Sub-Op207	Remove Motor for Material Recovery	-967 5	1 67	-	-967 5	1 7	0.015	-	1.75	0 8
	Sub-Op208	Remove Compressor for Material Recovery	-348 8	1 4	8	-348 8	3 2	0 015	-	0 578	0 85
	Sub-Op209	Remove Power Supply for reuse	-700	2 1	-	-700	1.1	0.015	-	0 541	0 75
	Sub-Op210	Remove LCD for further treatment	-	-	-	-	-	0 015	-	-	-
	Sub-Op211	Remove Transformer for Material Recovery	-745 8	2 07	-	-745 8	0 9	0 015	-	1 241	0 8
	Sub-Op212	Remove Heating Element for Material Recove	-147 6	1.4	-	-147.6	1.8	0 015	-	0 15	0.75
	Sub-Op213	Remove Other Materials	-550	1 95	-	-550	1	0 015	-	0 75	0.75
	Sub-Op301	Remove Concrete and send it to landfill	-3 8	2 4	15	2 4	1	-	0.025	-	1
	Sub-Op302	Remove Textile for Incineration	-60	1 1	-3 6	-3 6	0 1	-	0 025	-	1
	Sub-Op303	Remove Wood for Incineration	-39	4 2	-12	-12	0 5	-	0.025	-	1
	Sub-Op304	Remove PVC and send it to landfill	-270	2 8	37	2 8	0 5	-	0 035	-	1

Record: 276 of 276

Datasheet View — NUM

Figure 9.11: A process data table within the database module

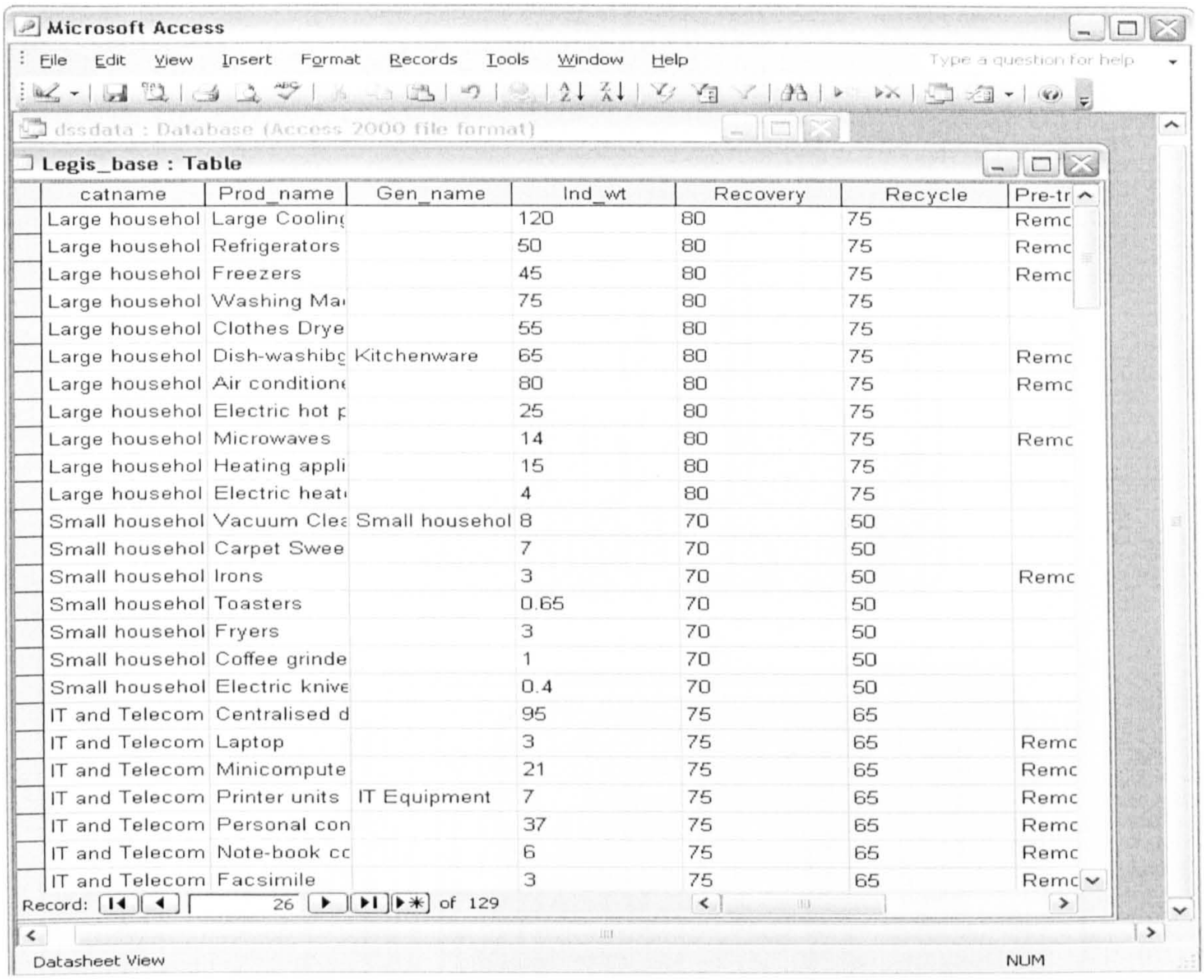


Figure 9.12: A legislative requirement table within the database module

The information collected and processed in the user interface module and the database module is used to support the remaining modules of CA***R***PP as described in the following sections of this chapter.

9.6 The Recycling Process Planning Module

The recycling process planning module generates the bespoked recycling process plans for WEEE based on the relevant information of the product under consideration, collected as part of the automated product evaluation task. The recycling process planning module is built around a central database which is linked to the other modules of the CA***R***PP as shown in Figure 9.13. The central database contains pre-defined standard recycling process plans for different categories of electrical and electronic equipment included in WEEE.

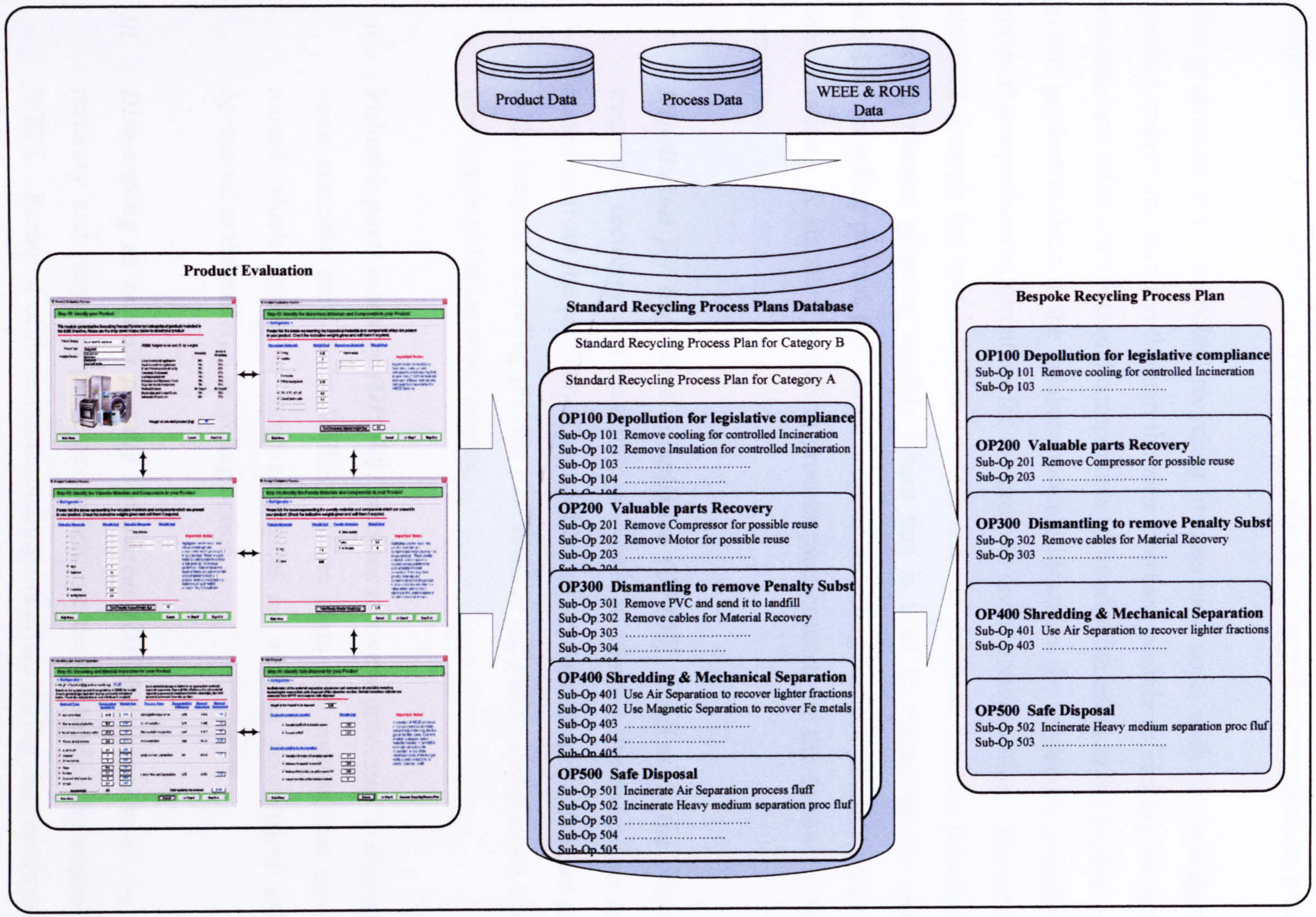


Figure 9.13: Interaction among various modules of the CA*R*PP to generate the recycling process plan

A standard recycling process plan for a specific category of electrical and electronic equipment consists of a wide range of recovery and recycling processes to cater for the variety of electrical and electronic products in that category together with broad range of components and substantial differences in material composition among those products.

The generation of the bespoked recycling process plan starts with the evaluation of the product under consideration through the user interface module to identify the hazardous, valuable and other materials and components of interest included in the product. Parallel to this product evaluation the database module identifies the legislative compliance and material composition information for the product under consideration. The information obtained through the user interface module and the database module is passed to the recycling process planning module where this is used to customise the appropriate standard recycling process plan into a bespoke recycling process plan for product under consideration. A standard recycling process plan consists of the following five main operations:

i. ***Depollution for legislative compliance (OP100):*** consists of the relevant pre-treatment recovery and recycling processes to remove the hazardous and toxic materials from the product. This addition of appropriate pre-treatment processes to the bespoke recycling process plan ensures legislative compliance in terms of meeting de pollution requirements.

ii. ***Valuable parts recovery (OP200):*** involves recovery processes to dismantle high value reusable parts from WEEE. These parts and components can then be reused which results in more ecological as well as economical gain when compared to the material recycling option.

iii. ***Dismantling to remove penalty substances (OP300):*** consists of the relevant recovery and recycling processes to remove the contaminating materials from WEEE. Removal of these contaminating materials during the pre fragmentation stage improves the subsequent material recovery and economical performance of product recycling.

iv. ***Shredding and mechanical separation (OP400):*** consists of various fragmentation processes and subsequent mechanical separation processes. The selection of these fragmentation and mechanical separation processes is controlled by the product characteristics and its material composition.

v. ***Safe disposal (OP500):*** consists of various disposal processes which allow proper disposal of un-recovered materials and wastes in WEEE recycling. Certain hazardous substances removed from WEEE also require safe disposal. In such cases the option of landfill will be assigned to certain materials in the WEEE which are not suitable for incineration in view of the toxic nature of their flue gas residues.

Each main operation in the standard recycling process plan consists of a number of relevant sub-operations i.e. specific recovery and recycling processes (e.g. Sub-Op101 – Sub-Op109 in Figure 9.14). These recovery and recycling processes are linked to different product design, material characteristics and legislative compliance requirements identified within the user interface module and the database module of the CA*R*PP. The addition of specific recovery and recycling processes under these main operations in the bespoke recycling process plan is controlled by product evaluation and legislative compliance monitoring information. For example, in the case of a refrigerator, the presence of insulation identified during product evaluation stage will trigger the addition of the specific recovery process related to the removal of insulation in the bespoke recycling process plan. Figure 9.14 shows a bespoke recycling process plan for a typical refrigerator generated through the CA*R*PP.

The recycling process plan shown in Figure 9.14 is split into three distinct areas. Firstly, the list on the top left corner outlines the identity of the product, its WEEE category, net product weight, total hazardous material weight, weight sent to the shredder, and weight disposed. This information acts as an identifier to retrieve the saved recycling process plan from the database. Secondly, the central area of the recycling process plan contains the five main recovery and recycling operations (OP100, OP200, etc.) along with the relevant sub-operations (Sub-Op101, Sub-Op102, etc.) together with material/component weight processed through them.

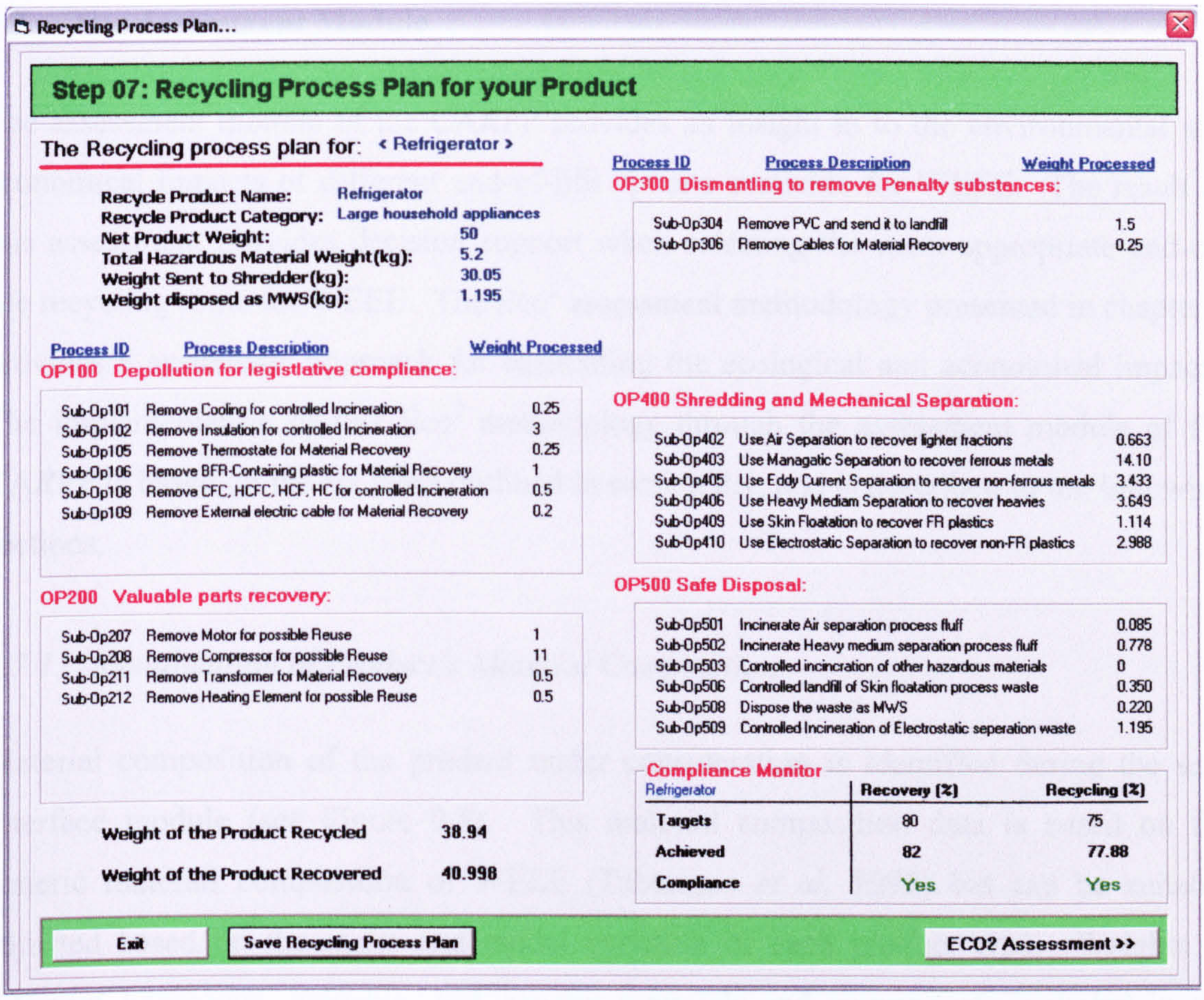


Figure 9.14: A typical recycling process plan for an end-of-life product

The recovery and recycling percentage achieved through recycling process plan is calculated by net product weight and weight processed by individual recovery and recycling processes. The sequence of operations in different recycling process plans to be followed for recycling of different products (Op100, OP200, OP300 and so on) remains the same, whereas the individual recovery and recycling sub operations within each main operation are product specific. Finally, on the bottom right corner is the compliance monitor which highlights the WEEE directive recovery and recycling targets along with the actual recovery and recycling percentage achieved through recycling process plan. Once a recycling process plan has been generated, the user can start the assessment module (see section 9.7) to calculate the environmental and economical impacts of various end-of-life options in order to identify the most appropriate recycling route for a specific product.

9.7 The Assessment Module

The assessment module of the CA*R*PP provides an insight in to the environmental and economical impacts of different end-of-life options available for WEEE. The result of this assessment provides decision support when selecting the most appropriate end-of-life recycling route for WEEE. The Eco^2 assessment methodology presented in chapter 8 provides a systematic approach for calculating the ecological and economical impacts. The implementation of this Eco^2 methodology through the assessment module of the CA*R*PP is based on the six tasks outlined in section 8.4, and is described in the following sections.

9.7.1 Identification of Product's Material Composition

Material composition of the product under consideration is identified during the user interface module (see Figure 9.8). This material composition data is based on the generic material composition of WEEE (Taberman *et al.* 1995) but can be suitably adjusted based on the make and model variation of each product type. Weights of different hazardous, valuable, and penalty materials and components included in the product are available from the recycling process plan (see Figure 9.14).

9.7.2 Identification of Different End-of-Life Options

The assessment module generally considers the following three end-of-life options for Eco^2 assessment.

i. *Recycling through shredding after depollution*: This option involves shredding the depolluted product into small fractions and using mechanical separation processes (air separation, magnetic separation, eddy current separation, dense media separation etc) to recover different materials. Depollution involves removal of different hazardous materials and components included in the product.

ii. *Recycling through recycling process plan*: This option involves recycling of the product through a bespoke five stage recycling process plan. Figure 9.14 shows a bespoke recycling process plan for an end-of-life product (see section 9.6) to be used for Eco^2 assessment.

iii. *Landfilling:* This option involves disposal of the complete product to landfill.

The above mentioned end-of-life options represents the current end-of-life recycling practices for WEEE along with the novel recycling process plan option. Additionally, the user can define other end-of-life options for a particular product to be assessed through the assessment module.

9.7.3 Calculation of the Performance Limits

The ecological and economical performance limits for the product are based on its material composition. Figure 9.15 and 9.16 highlights the calculation of these performance limits through the CA*R*PP. The performance limits provide a scale for the evaluation and assessment of the actual ecological and economical performance of different end-of-life options available for product recycling. It should be noted that the upper performance limit represents ecological gain (usually a negative mPt value) whereas the lower performance limit represents ecological impact (usually a positive mPt value). Equations (8.1) and (8.3) (see section 8.4.3) are used to calculate ecological performance limits for a specific product.

$$Upper\ limit\ of\ ecological\ performance = BCS_{ecol} = \sum_{i}^{n}(m_i \times EIi_{BCS}) = -14131.84mPt$$

$$Lower\ limit\ of\ ecological\ performance = WCS_{ecol} = \sum_{i}^{n}(m_i \times EIi_{WCS}) = 103.21mPt$$

Similarly, Equations (8.2) and (8.4) are used to calculate the economical performance limits. It should be noted that negative value for upper economical performance represents revenue from product recycling and positive value represents a cost burden.

$$Upper\ limit\ of\ economical\ performance = BCS_{econ} = \sum_{i}^{n}(m_i \times CIi_{BCS}) = -£14.58$$

$$Lower\ limit\ of\ economical\ performance = WCS_{econ} = \sum_{i}^{n}(m_i \times CIi_{WCS}) = £12.01.$$

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Refrigerator >

Upper and Lower Limits of Environmental Performance for < Refrigerator >

Recycle Product Name: < Refrigerator > Net Product Weight: 50

An upper and lower limit of end-of-life Environmental Performance is calculated to evaluate the environmental performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg)		mi x Eli bcs (mPt)	mi x Eli wcs (mPt)
		Material Substitution (Eli bcs)	Landfill (Eli wcs)		
Steel	23.95	-86	1.4	-2059.7	33.53
FR Plastics	2.65	-383.3	3.95	-1015.74	10.47
NFR Plastics	7.65	-383.3	3.95	-2932.25	30.22
Wood / Plywood	1.3	-39	4.2	-50.7	5.46
Aluminium	2.35	-780	1.4	-1833	3.29
Copper	3.5	-1400	1.4	-4900	4.9
Other matels	0.5	-1150.9	1.4	-575.45	0.7
Glass	2.7	-66	1.4	-178.2	3.78
Rubber	0.55	-360	7.4	-198	4.07
Concrete	1	-3.8	1.4	-3.8	1.4
Others	3.85	-100	1.4	-385	5.39

Upper limit of Ecological Performance = -14131.84

Lower limit of Ecological Performance = 103.21

Upper limit of environmental performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any environmental burden of treatment processes."

Lower limit of environmental performance is calaculated considering that every material in the Product is ending up in the landfill without any environmental burden of treatment processes."

Exit | Recycling Process Plan | Step 2 >>

Figure 9.15: Calculation of ecological performance limits

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Refrigerator >

Upper and Lower Limits of Economical Performance for < Refrigerator >

Recycle Product Name: < Refrigerator > Net Product Weight: 50

An upper and lower limit of end-of-life Economical Performance is calculated to evaluate the economical performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg)		mi x Cli bcs (£)	mi x Cli wcs (£)
		Material Revenue (Cli bcs)	Disposal Cost (Cli wcs)		
Steel	23.95	0.07	0.03	1.68	0.72
FR Plastics	2.65	0.1	0.03	0.26	0.08
NFR Plastics	7.65	0.1	0.03	0.77	0.23
Wood / Plywood	1.3	0	0.03	0	0.04
Aluminium	2.35	0.8	0.03	1.88	0.07
Copper	3.5	2.8	0.03	9.8	0.1
Other matels	0.5	0.1	0.03	0.05	0.02
Glass	2.7	0.03	0.03	0.08	0.08
Rubber	0.55	0.1	0.03	0.06	0.02
Concrete	1	0	0.03	0	0.03
Others	3.85	0	0.03	0	0.12

Upper limit of Economical Performance = -14.58

Lower limit of Economical Performance = 12.01

Cost of Depollution = 10.5

Upper limit of economical performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any economical burden of treatment processes."

Lower limit of economical performance is calaculated considering that every material in the Product is ending up in the landfill."

Exit | Recycling Process Plan | Step 2 >>

Figure 9.16: Calculation of economical performance limits

9.7.4 *Calculation of the Actual Performance of Different End-of-Life Options*

The calculation of the actual performance of 'recycling through shredding after depollution' option within the assessment module of the CA*R*PP is illustrated in Figure 9.17 and 9.18. Weights of different materials contained in the product are calculated using the material composition data in Figure 9.8.

Ecological and economical impacts associated with different material streams in this end-of-life option together with the data on process efficiencies and material grades are retrieved from the database module. Based on the end-of-life destination of each material, an ecological impact value and costs are assigned to individual materials contained in the product.

Equations (8.5) and (8.6) (see section 8.4.4) are used within the assessment module to calculate the actual ecological and economical performance of the product through shredding option, as outlined below:

Actual ecological performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -6036mPt$$

Actual economical performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £3.77$$

Similarly, the calculation of the actual performance of 'Recycling through recycling process plan' option within the assessment module of the CA*R*PP is illustrated in Figure 9.19 and 9.20. Recycling process plan contains bespoke recovery and recycling processes for the end-of-life treatment of the product under consideration. Based on the end-of-life destination of each material, an ecological impact value and various end-of-life costs are assigned to individual processes contained in the recycling process plan for the product.

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Refrigerator >

Environmental Impact Assessment of the current recycling practice for < Refrigerator >

Recycle Product Name: < Refrigerator > Hazardous Materials Weight: 5.2 Shredding Weight: 44.8

End-of-life environmental performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) (Eli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
		Material Substitution	Landfill	Incineration			
Steel	21.46	-86	-	-	0.95	0.8	-1402.63
FR Plastics	2.37	-	3.95	-	1	1	9.36
NFR Plastics	6.85	-383.3	-	-	0.70	0.6	-1102.75
Wood / Plywood	1.16	-	-	-12	1	1	-13.92
Aluminium	2.11	-780	-	-	0.85	0.65	-909.3
Copper	3.14	-1400	-	-	0.85	0.7	-2615.62
Other metals	0.45	-	-	-32	1	1	-14.4
Glass	2.42	-	1.4	-	1	1	3.39
Rubber	0.49	-	7.4	-	1	1	3.63
Concrete	0.9	-	1.4	-	1	1	1.26
Others	3.45	-	1.4	-	1	1	4.83

Actual Ecological Performance = -6036.15

Exit | Recycling Process Plan | Step 3 >>

Figure 9.17: Calculation of actual ecological performance through shredding option

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Refrigerator >

Economical Impact Assessment of the current recycling practice for < Refrigerator >

Recycle Product Name: < Refrigerator > Hazardous Materials Weight: 5.2 Shredding Weight: 44.8

End-of-life economical performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Cli ap x PEi x Gi (£)
		Processing Cost	Disposal Cost	Material Revenue			
Steel	21.46	0.02	-	0.07	0.95	0.8	-0.82
FR Plastics	2.37	0.025	0.015	-	1	1	0.09
NFR Plastics	6.85	0.025	-	0.1	0.70	0.6	-0.22
Wood / Plywood	1.16	0.018	0.015	-	1	1	0.04
Aluminium	2.11	0.028	-	0.8	0.85	0.65	-0.9
Copper	3.14	0.030	-	2.8	0.85	0.7	-5.18
Other metals	0.45	0.030	0.015	-	1	1	0.02
Glass	2.42	0.024	0.015	-	1	1	0.09
Rubber	0.49	0.024	0.015	-	1	1	0.02
Concrete	0.9	0.015	0.015	-	1	1	0.03
Others	3.45	0.015	0.015	-	1	1	0.1

Actual Economical Performance = -6.73

Cost of Depollution = 10.5

Exit | Recycling Process Plan | Step 3 >>

Figure 9.18: Calculation of actual economical performance through shredding option

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Refrigerator >

Environmental Impact Assessment of the Proposed Recycling Process Plan for < Refrigerator >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Environmental Impact (mPt/kg) (Eli ap)				Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
			Material Substitution	Landfill	Incineration	Actual		
Sub-Op101	Remove Cooling for controlled Incineration	0.25	-160	16	46	46	1	11.5
Sub-Op102	Remove Insulation for controlled Incineration	3	-480	8	2.8	2.8	1	8.4
Sub-Op105	Remove Thermostate for Material Recovery	0.25	-363.6	1.4	-63.2	-363.6	0.85	-77.26
Sub-Op106	Remove BFR-Containing plastic for Material Recovery	1	-360	1.4	-5.3	-360	0.7	-252
Sub-Op108	Remove CFC, HCFC, HCF, HC for controlled Incineration	0.5	-240	24	-36	-36	1	-18
Sub-Op109	Remove External electric cable for Material Recovery	0.2	-1079	2.14	-82.7	-1079	0.75	-161.85

Valuable Recovery

Sub-Op207	Remove Motor for Material Recovery	1	-967.5	1.67	-	-967.5	0.8	-774
Sub-Op208	Remove Compressor for Material Recovery	11	-348.8	1.4	8	-348.8	0.85	-3261.28
Sub-Op211	Remove Transformer for Material Recovery	0.5	-745.8	2.07	-	-745.8	0.8	-298.32
Sub-Op212	Remove Heating Element for Material Recovery	1	-147.6	1.4	-	-147.6	0.75	-110.7

Penalty Removal

Sub-Op304	Remove PVC and send it to landfill	1.5	-270	2.8	37	2.8	1	4.2
Sub-Op306	Remove Cables for Material Recovery	0.5	-1079	2.15	-	-1079	0.75	-404.62

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0.646	-39	4.2	-12	-12	0.75	-5.81
Sub-Op403	Use Managatic Separation to recover ferrous metals	13.74	-86	1.4	-32	-86	0.8	-945.31
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	3.348	-1105.9	1.4	-110	-1150.9	0.65	-2504.59
Sub-Op406	Use Heavy Mediam Separation to recover heavies	3.559	-89.4	2.4	6.9	-89.4	0.6	-190.9
Sub-Op409	Use Skin Floatation to recover FR plastics	1.086	-383.4	3.95	37	3.85	0.6	2.51
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	2.913	-383.4	3.95	-13	-383.3	0.6	-669.93

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0.083	-	4.2	-12	-12	1	-1
Sub-Op502	Incinerate Heavy medium separation process fluff	0.759	-	2.4	6.9	6.9	1	5.24
Sub-Op503	Controlled incincration of other hazardous materials	0	-	7.83	-20.8	-20.8	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.341	-	3.95	37	3.95	1	1.35
Sub-Op508	Dispose the waste as MWS	0.214	-	1.4	-15	-15	1	-3.21
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	1.165	-	3.95	-13	-13	1	-15.14

Actual Ecological Performance = -9660.72

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure 9.19: Calculation of actual ecological performance of recycling through recycling process plan

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Refrigerator >

Cost/Benefit Analysis of the Proposed Recycling Process Plan for < Refrigerator >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)				Grade (Gi)	mi x Cli ap x PEi x Gi (£)
			Disassembly Cost	Processing Cost	Disposal Cost	Material Revenue		
Sub-Op101	Remove Cooling for controlled Incineration	0.25	0.7	-	0.025	-	1	0.71
Sub-Op102	Remove Insulation for controlled Incineration	3	1.6	-	0.025	-	1	1.68
Sub-Op105	Remove Thermostate for Material Recovery	0.25	0.9	0.015	-	0.362	0.85	0.83
Sub-Op106	Remove BFR-Containing plastic for Material Recovery	1	1.8	0.015	-	0.2	0.7	1.67
Sub-Op108	Remove CFC, HCFC, HCF, HC for controlled Incineration	0.5	2.9	-	0.025	-	1	2.91
Sub-Op109	Remove External electric cable for Material Recovery	0.2	0.1	0.015	-	1.1	0.75	0.06

Valuable Recovery

Sub-Op207	Remove Motor for Material Recovery	1	1.7	0.015	-	1.75	0.8	0.31
Sub-Op208	Remove Compressor for Material Recovery	11	3.2	0.015	-	0.578	0.85	2.06
Sub-Op211	Remove Transformer for Material Recovery	0.5	0.9	0.015	-	1.241	0.8	0.41
Sub-Op212	Remove Heating Element for Material Recovery	1	1.8	0.015	-	0.15	0.75	1.7

Penalty Removal

Sub-Op304	Remove PVC and send it to landfill	1.5	0.5	-	0.035	-	1	0.55
Sub-Op306	Remove Cables for Material Recovery	0.5	0.1	0.015	-	1.1	0.75	0.31

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0.646	-	0.018	0.015	0	1	0.02
Sub-Op403	Use Managatic Separation to recover ferrous metals	13.74	-	0.02	0	0.07	0.8	0.55
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	3.348	-	0.03	0	1.99	0.65	4.27
Sub-Op406	Use Heavy Mediam Separation to recover heavies	3.559	-	0.025	0.015	0	1	0.14
Sub-Op409	Use Skin Floatation to recover FR plastics	1.086	-	0.025	0.015	0	1	0.04
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	2.913	-	0.025	0	0.1	0.6	0.13

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0.083	-	0.018	0.015	0	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.759	-	0.025	0.015	0	1	0.03
Sub-Op503	Controlled incincration of other hazardous materials	0	-	0.015	0.025	0	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.341	-	0.025	0.015	0	1	0.01
Sub-Op508	Dispose the waste as MWS	0.214	-	0.025	0.015	0	1	0.01
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	1.165	-	0.025	0.015	0	1	0.05

Actual Economical Performance = -3.69

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure 9.20: Calculation of actual economical performance of recycling through recycling process plan

For the recycling of sub-assemblies and components contained in the product, sensible assumptions about their material composition are made to calculate their ecological and economical impacts. For example in case of the material substitution value (ecological impact value of primary virgin material extraction that is actually substituted by recycled material and must therefore not be extracted) for external electric cable (-1079mPt), it is assumed that the cable contains 70% of copper and 30% polyethylene. Using the individual material substitution values of copper (-1400mPt) and polyethylene (-330mPt), the material substitution value for cable is calculated (0.7x-1400 + 0.3 x -330 = -1079 mPt). Similar technique is used to calculate the costs and benefits involved in the recycling activities for other sub-assemblies and components. Equations (8.5) and (8.6) are used within the assessment module to calculate the actual ecological and economical performance for the product through recycling process plan option, as outlined below.

Actual ecological performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -9660mPt$$

Actual economical performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = -£3.69$$

9.7.5 Comparison of the Performance of Different End-of-Life Options

The comparison of the performance of different end-of-life options within the assessment module of the CA*R*PP is illustrated in Figure 9.21. This comparison evaluates the actual ecological and economical performance with the respective performance limits. The closer the actual performance is to the upper performance limit the better is the assessed end-of-life option. The screenshot in Figure 9.21 illustrates this comparison for a refrigerator. It is to be noted that by definition the lower performance limit represents the end-of-life performance of the product which is based on the landfilling option.

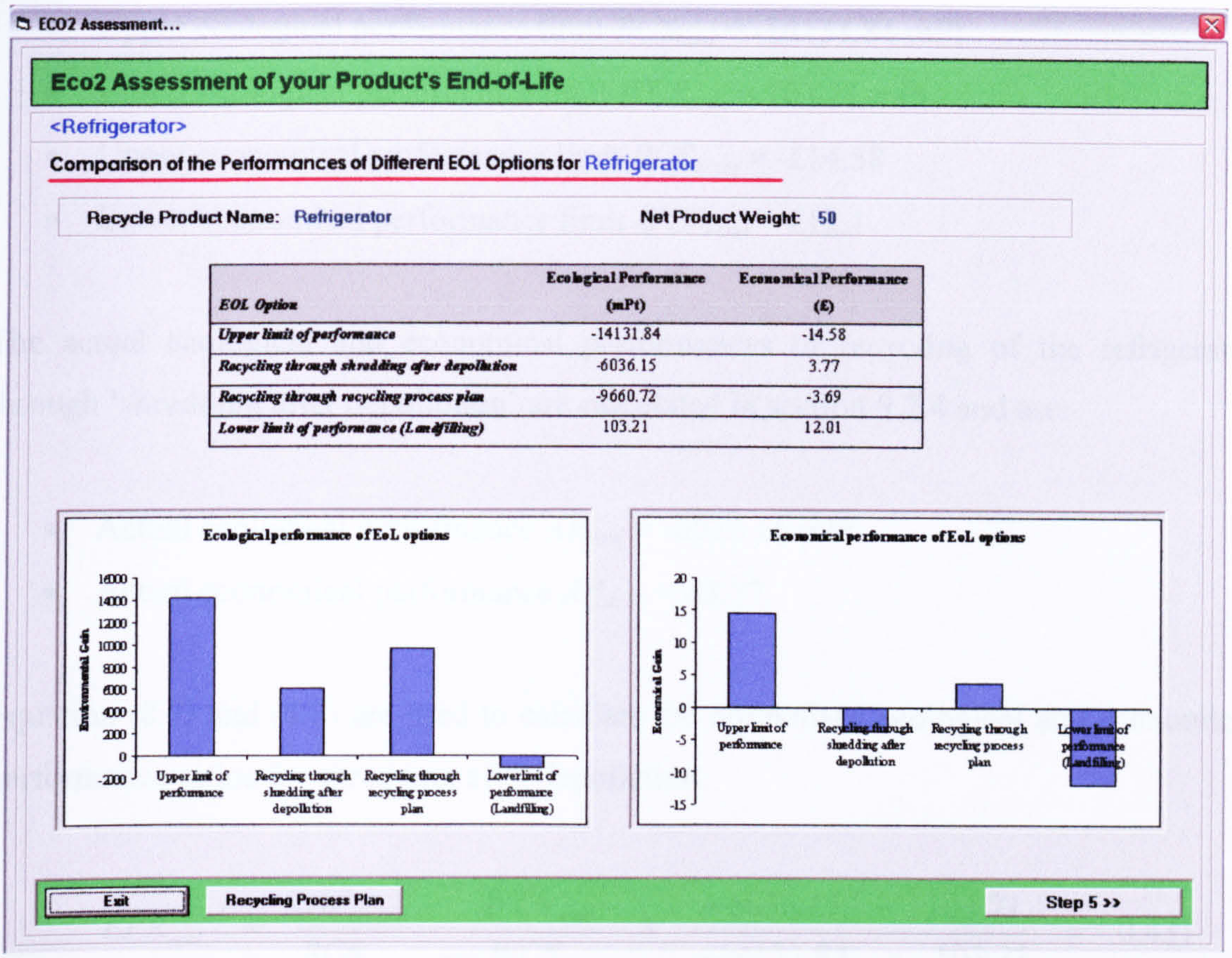


Figure 9.21: Comparison of performances of different end-of-life options for refrigerator

9.7.6 Generation of the Combined Ratios for Ranking Different End-of-Life Options

Finally, the combined Eco^2 performance ratios of different end-of-life options providing an overview of their ecological and economical performances are calculated within the assessment module of the CA***R***PP. As the environmental concerns and the economical concerns are considered equally important in this research (the emphasis can be changed by giving different coefficients to ecological and economical performance ratios in Equation 8.9), the combined Eco^2 performance ratio (C***E***PR) is calculated by taking average of the ecological performance ratio (EPR_{ecol}) and the economical performance ratio (EPR_{econ}). For the refrigerator, the calculation of EPR_{ecol} and EPR_{econ} and finally C***E***PR for different end-of-life options is outlined below.

The upper and lower performance limits for the refrigerator are calculated in section 9.7.3 and are:

- Upper ecological performance limit BCS_{ecol} = -14131.84 mPt
- Lower ecological performance limit WCS_{ecol} = 103.21 mPt
- Upper economical performance limit BCS_{econ} = -£14.58
- Lower economical performance limit WCS_{econ} = £12.1

The actual ecological and economical performances of recycling of the refrigerator through 'shredding after depollution' are calculated in section 9.7.4 and are:

- Actual ecological performance AP_{ecol} = -6036.15 mPt
- Actual economical performance AP_{econ} = £3.77

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for shredding after depollution.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-6036.15 - 103.21}{-14131.84 - 103.21} = 0.431$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{3.77 - 12.1}{-14.58 - 12.1} = 0.309$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.431 + 0.309}{2} = 0.37$$

Similarly, the actual ecological and economical performances of recycling of the refrigerator through 'recycling process plan option' are calculated in section 9.7.4 and are:

- Actual ecological performance AP_{ecol} = -9660.72 mPt
- Actual economical performance AP_{econ} = -£3.69

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for recycling process plan option.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-9660.72 - 103.21}{-14131.84 - 103.21} = 0.686$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{-3.69 - 12.1}{-14.58 - 12.1} = 0.59$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.686 + 0.59}{2} = 0.638$$

The ecological and economical performance ratios along with the combined performance ratio of different end-of-life options for the refrigerator are summarised in Table 9.1. C*E*PR ranges from '0' to '1', with '0' being the lower performance limit (worst case scenario) and '1' being the upper performance limit (best case scenario) (see section 8.4.6 for these calculations). As the higher value of C*E*PR (close to 1) represents a good overall performance of the assessed end-of-life option, it can be concluded that the overall performance of the recycling process plan option (C*E*PR = 0.638) is better than the shredding after depollution option (C*E*PR = 0.37). Figure 9.22 depicts the ranking of different end-of-life options for the refrigerator in relation to the best and worst case scenario. The functionality of the CA*R*PP is further tested and demonstrated in the case studies in chapter 10.

EOL Option	**Ecological Performance Ratio (EPR_{ecol})**	**Economical Performance Ration (ERP_{econ})**	**Combined Eco^2 Performance Ratio (C*E*PR)**
Upper limit of performance	1	1	**1**
Shredding after depollution option	0.431	0.309	**0.37**
Recycling process plan option	0.686	0.59	**0.638**
Lower limit of performance	0	0	**0**

. **Table 9.1:** Performance ratios for different end-of-life options for refrigerator

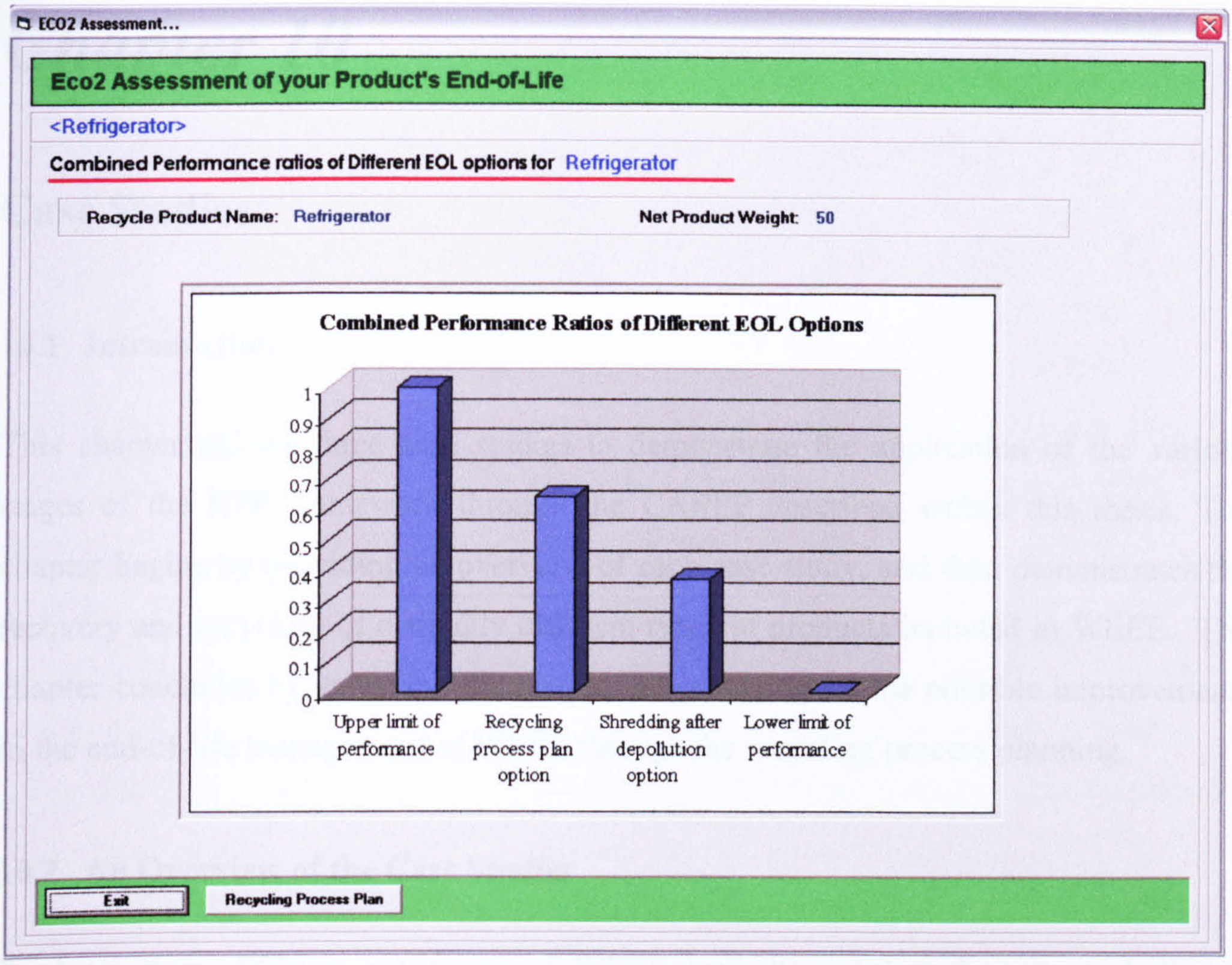


Figure 9.22: Overall ranking of different end-of-life options for refrigerator

9.8 Chapter Summary

This chapter has described a prototype computer aided recycling process planner which has been developed in order to support the application of the recycling process planning framework as well as the ecological and economical assessment methodology devised in this research. Different modules of the CA***R***PP, namely user interface module, database module, recycling process planning module, and assessment module implementing various stages of the RPP framework and Eco^2 methodology are detailed.

It is proposed that the utilisation of CA***R***PP within the electrical and electronic recovery facilities can increase value recovery, introduce process consistency and improve the development of bespoke recycling process plans which are based on the most updated product information and knowledge related to existing recycling processes. Three case studies have been undertaken in chapter 10 to validate the effectiveness of the CA***R***PP and the associated research reported in this thesis.

Chapter 10

Case Studies

10.1 Introduction

This chapter utilises three case studies to demonstrate the application of the various stages of the RPP framework through the CA*R*PP described within this thesis. The chapter begins by providing an overview of each case study, and then demonstrates the recovery and recycling of distinctly different types of products included in WEEE. The chapter concludes by analysing the results and reflecting on the possible improvements in the end-of-life management of WEEE through the recycling process planning.

10.2 An Overview of the Case Studies

Products from different categories of WEEE have been selected as case studies to provide a broader perspective for the evaluation of research concepts. The main objective from these case studies was to firstly demonstrate the application of new knowledge developed by this research, secondly to provide a means of comparison between current practices and those suggested through application of the CA*R*PP, and finally to validate that theoretical values (e.g. weights of products and their components, and ecological and economical impacts) generated through CA*R*PP are approximately equal to the practical values generated through dismantling experiments. Therefore, the author carried out three case studies. The first product is a 'microwave oven' which belongs to the large household appliances category in the WEEE directive. It provides a typical example of a metal dominated product with low hazardous content which is quite attractive for the current recovery and recycling operators, due to its low depollution requirements and high potential hidden value. The second product is a personal computer (central processing unit, mouse, screen and keyboard included) consisting of a variety of materials and components including hazardous substances. Specific pre-treatment requirements have been established for the screen (cathode ray tube) in the WEEE directive. The recovery and recycling of the computer is more complex and problematic than the microwave oven. In contrast, the third product is an 'electrical

kettle' which belongs to the small household appliances category. It is a typical example of a product mainly based on non-metallic materials, hence very difficult to justify the commercial viability of its recycling. It should be noted that a kettle is not classified as hazardous waste under the WEEE directive.

10.3 Case Study 1: Microwave Oven

The product considered as the first case study is a microwave oven. Microwave oven uses various combinations of electrical circuits and mechanical devices to produce and control an output of microwave energy for heating and cooking. Generally, the electronic and electrical systems of a microwave oven can be divided into two fundamental sections, the control section and the high-voltage section. The control section consists of a timer (electronic or electromechanical), a system to control or govern the power output, and various interlock and protection devices. The components in the high-voltage section serve to step up the standard voltage (220-240V) to high voltage. The high voltage is then converted into microwave energy. The microwave oven (see Figure 10.1) has been selected as a case study as it belongs to large household appliance category of WEEE. The large household appliance category, consisting mainly of metal dominated products for which recovery practices are currently established together with other large goods like vehicles, represents the biggest proportion (by weight) of WEEE. In the following sections different stages of the recycling process planning framework namely product evaluation, legislative compliance monitoring, recycling process planning and Eco^2 assessment are applied to this case study product to demonstrate their applicability in end-of-life product recovery and recycling.

Figure 10.1: Case study 1: Microwave oven

It is to be noted that the RPP framework stages are implemented through the associated software tool, namely the CA*R*PP.

10.3.1 Product Evaluation

The first stage in applying the RPP framework is to identify the main characteristics and material composition of the microwave oven through a product evaluation stage. The product evaluation process consists of various identification tasks which are described below.

10.3.1.1 Identification of the Product and its Category

As already stated the microwave oven belongs to large household appliance category of WEEE. Once the product has been identified, the CA*R*PP highlights the WEEE directive recovery and recycling targets together with the average weight for the microwave oven (see Figure 10.2). The CA*R*PP allows users to change this net product weight if needed. In this case, the average product weight (i.e. 16 kg) is changed to the exact weight of the microwave oven under consideration (i.e. 11.4 kg).

10.3.1.2 Identification of Hazardous Materials and Components

The second task in the product evaluation identifies the hazardous materials and components included in the microwave oven. Fluorescent lamp and the external electric cable are highlighted together with their indicative weights as the hazardous components which need to be removed from the microwave in order to comply with the pre-treatment requirements of the WEEE directive, as shown in Figure 10.3. In the case of the microwave oven, another component known as the magnetron is considered hazardous in nature. Some of the magnets found in magnetrons can be made from samarium-cobalt which presents significant fire hazard due to its low temperature ignition point. The flexibility offered through the CA*R*PP to manually add more hazardous components and materials, as well as the ability to alter the weights of highlighted materials and components, allows users to customise this identification process for a specific product. The identification of the hazardous materials and components trigger the addition of the appropriate pre-treatment processes in the recycling process plan generated for the microwave oven (see Figure 10.8).

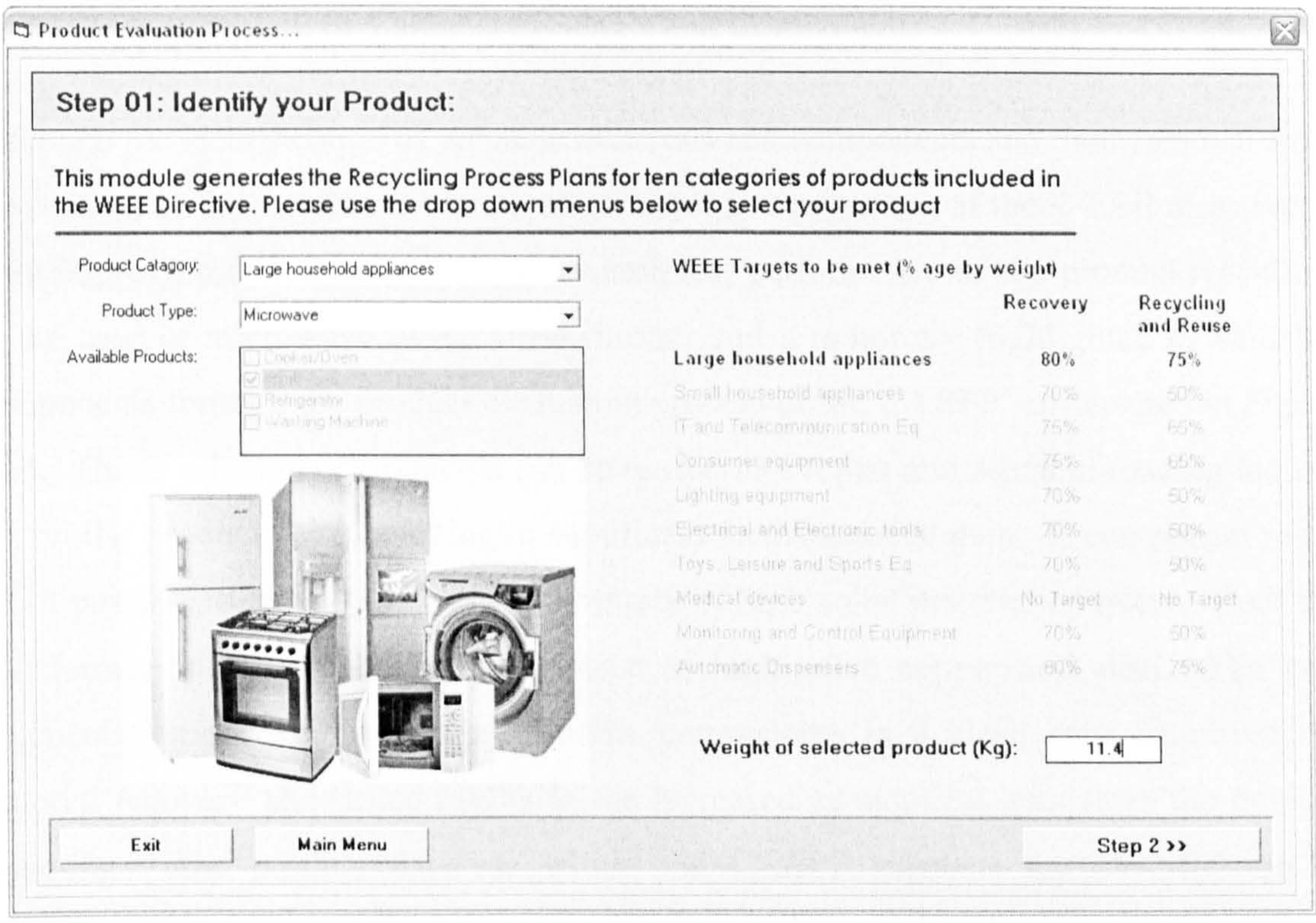


Figure 10.2: Identification of the case study product and its WEEE category

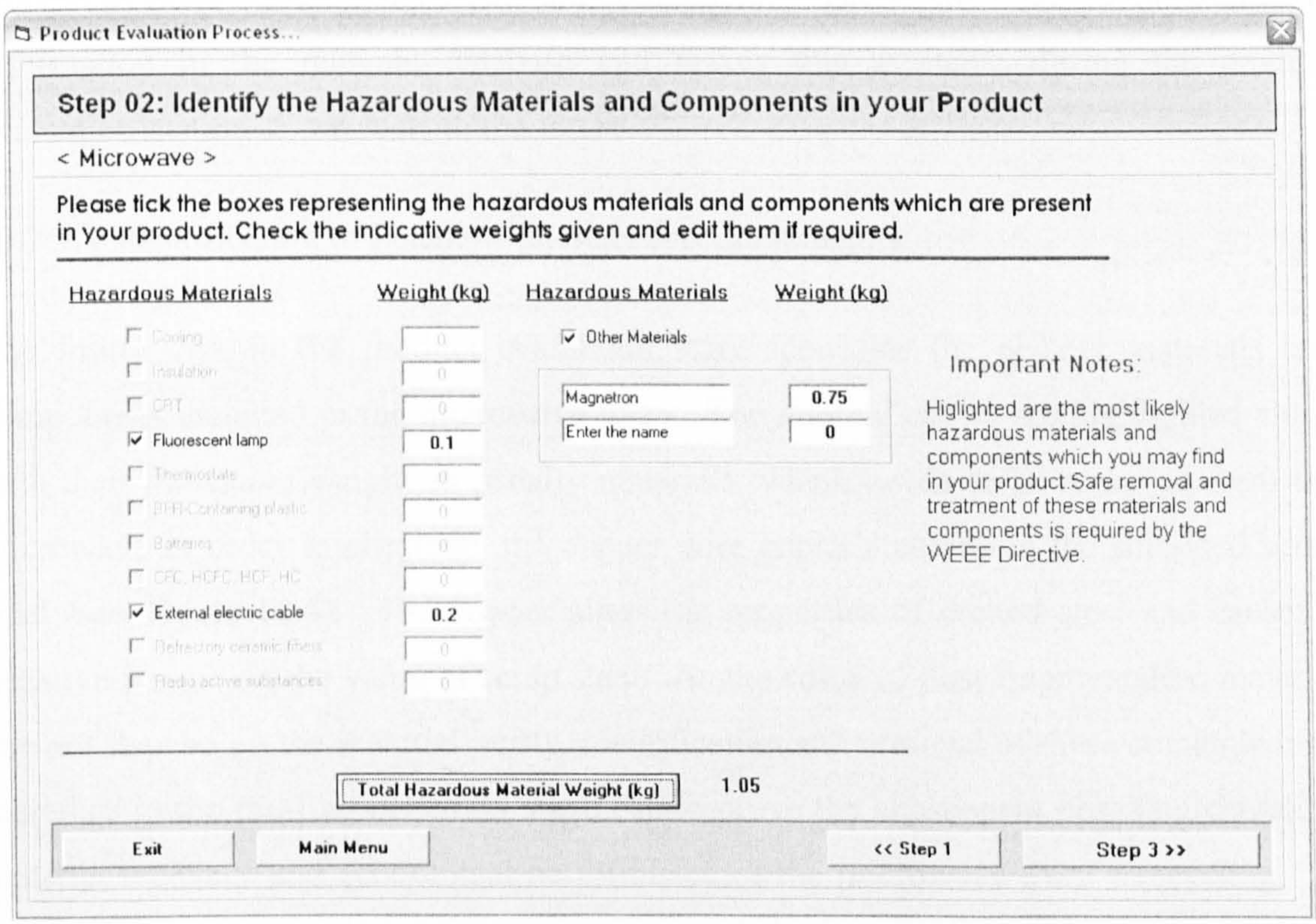


Figure 10.3: Hazardous materials in the microwave oven

10.3.1.3 Identification of Valuable Materials and Components

Although the identification of valuable materials and components and their removal from the product in the pre-fragmentation stage is not a requirement of the WEEE directive, it does improve the environmental and economical performance of the product recycling. In the case of microwave oven, a transformer and a motor are highlighted as valuable components through the product evaluation process of the CA*R*PP, as depicted in Figure 10.4. These valuable components can be reused in a repair and remanufacturing facility for similar products thus resulting in significant environmental gain. If component reuse is not possible, they still offer the opportunity of high value material recovery. Both the transformer and the motor mainly consist of high value copper and steel. The pre-fragmentation recovery of these valuable components in a clean state improves the material recovery and hence results in the increased economical gain from the product recycling. The product database within the CA*R*PP supports the identification of different valuable materials and components and their typical weights found in the wide range of electrical and electronic products included in WEEE. A second motor used to rotate the tray in microwave oven is manually added during the product evaluation process as other valuable materials and components. The CA*R*PP stores the additional information in the relevant database and makes this available during the product evaluation of similar products in the future.

10.3.1.4 Identification of Penalty Materials and Components

The fourth task in the product evaluation stage identifies the penalty materials and components included in the microwave oven. The internal cables are highlighted along with their indicative weight as penalty materials, which needs to be removed from the microwave in order to eliminate the copper wire contaminations in the shredded scrap steel (see Figure 10.5). The copper alters the properties of melted steel and causes a negative impact on the value of scrap steel. As the value of post fragmentation material streams depend on the material purity, identification and removal of these contaminating materials in the pre-fragmentation stage can improve the subsequent post fragmentation material recovery and economical performance of the microwave oven's recycling. In addition, there is a strong potential of reuse of these internal cables for the possible repair and refurbishing purposes.

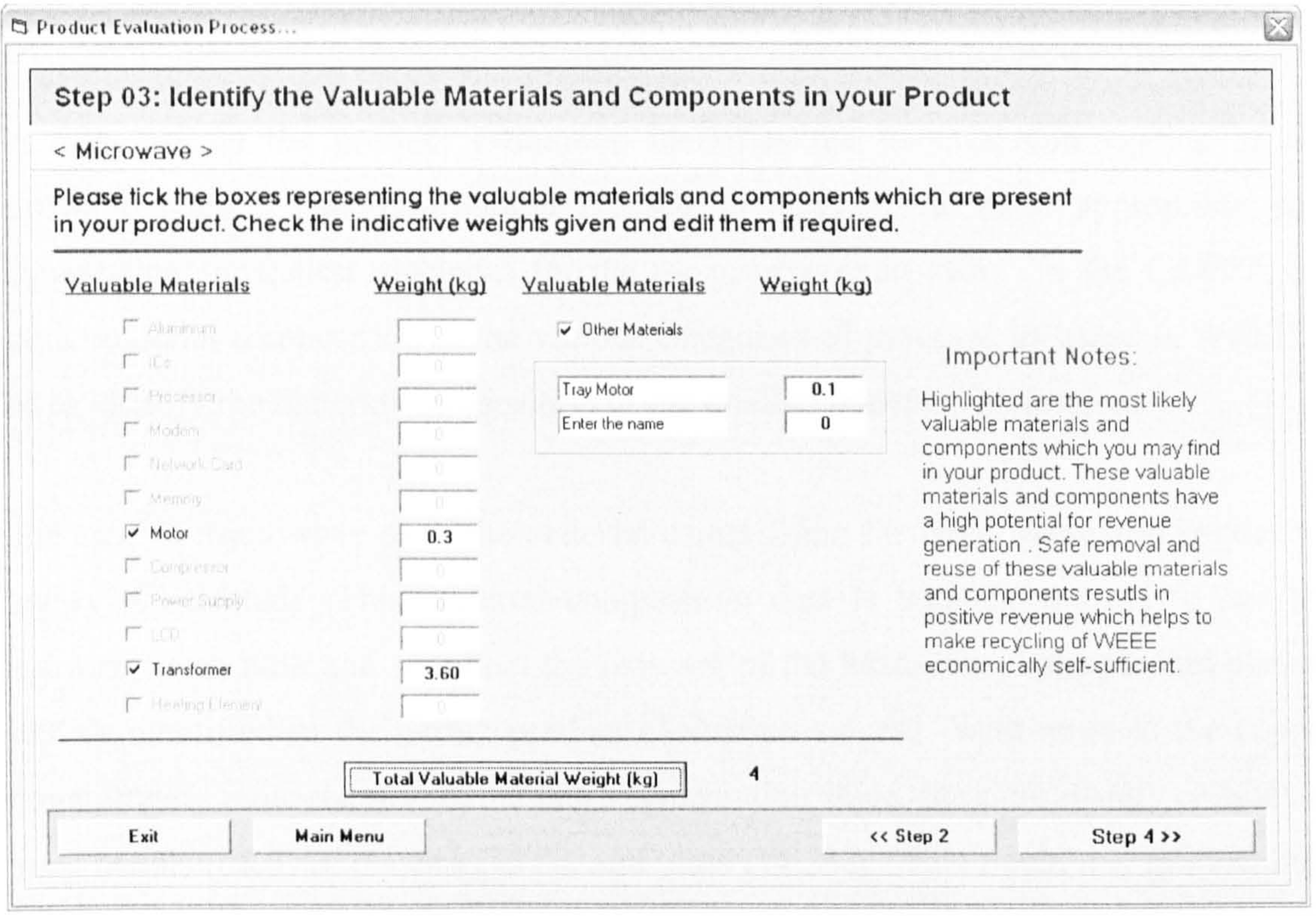


Figure 10.4: Valuable materials in the microwave oven

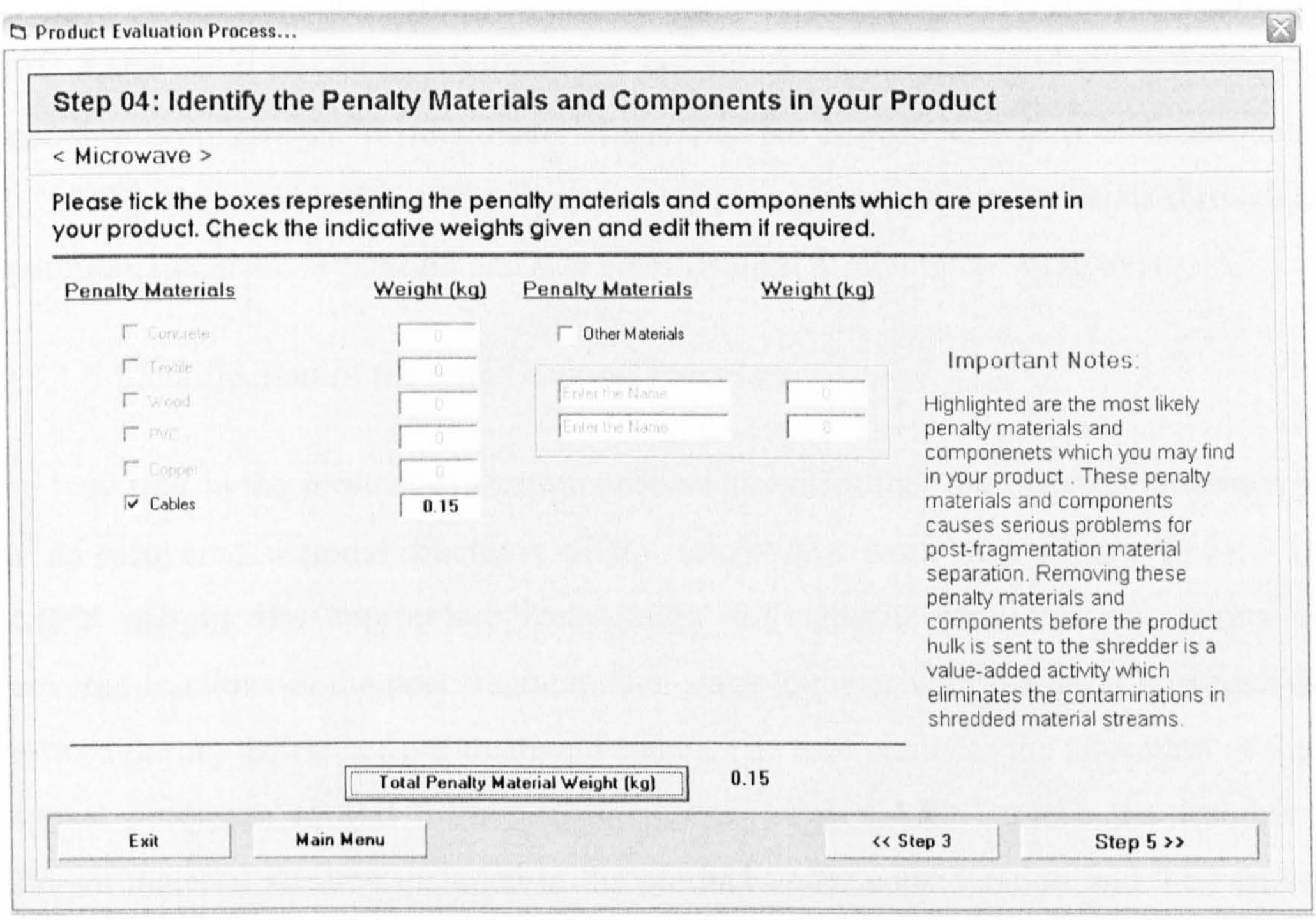


Figure 10.5: Penalty materials in the microwave oven

10.3.1.5 Identification of Material Composition and Post Fragmentation Separation

The fifth task in the product evaluation identifies the material composition of the microwave oven. This information is used to identify the most appropriate post fragmentation separation processes for the microwave oven hulk. In the CA*R*PP, the generic material composition of the various categories of products included in WEEE is used to identify the material composition of the product under consideration.

In the case of microwave oven the material composition for large household appliances category is selected. This material composition data is then customised to suit the microwave oven hulk and to reflect the removal of the hazardous, valuable and penalty materials identified in the earlier product evaluation stages. With most of the copper content already removed during the pre-fragmentation stage, the hulk mainly consists of ferrous metals (68.5%), plastics (13%), and glass (14.2%). This remaining product hulk is broken down to small fist size pieces in a fragmentation process to facilitate the subsequent material recovery. The screenshot in Figure 10.6 displays the material composition and the post fragmentation distribution of various material streams within the microwave oven hulk. Statistics originating from three academic studies (Iuga *et al.* 2001; Ambrose *et al.* 2002; Weatherhead and Hulse 2005) relating to the efficiency of separation processes for various material streams, are employed as part of functionality of CA*R*PP system to indicate the separation of post fragmentation materials through air separation, magnetic separation and size classification for the microwave oven..

10.3.1.6 Identification of the Safe Disposal Processes

The final task in the product evaluation process identifies the safe disposal processes for the un-recovered material fractions of the microwave oven (see Figure 10.7). The CA*R*PP assigns the appropriate incineration and landfill processes to various un-recovered fractions in the post fragmentation stage together with the hazardous fractions removed during the earlier pre-treatment stage. The user can alter the allocation of these disposal processes to suit his/her requirements. The CA*R*PP tracks the weights of different material streams included in the product under consideration and their end-of-life destinations in order to calculate the recovery and recycling targets achieved via different end-of-life options.

Product Evaluation Process ...

Step 05: Shredding and Material Separation for your Product

< Microwave >

>> Weight of product before shredding (Kg): 6.2

Based on the generic material composition of WEEE the weight of each material type included in your product is calculated below. Check the weights below and edit them if required.

Each material stream is linked to an appropriate material separation process. Separability efficiency of each material separation process is considered before calculating the total material recovered from the product.

Material Type	Composition (weight %)	Weight (kg)	Process Type	Separatability Efficiency	Material Processed	Material Recovered
☑ Iron and steel	68.5	4.247	Managatic Separation	0.98	4.247	4.162
☑ Flame retarded plastics	1.99	0.120	Skin Floatation	0.70	0.12	0.084
☑ Non-Flame retarded plastics	10.72	0.637	Electrostatic Separation	0.65	0.637	0.414
☐ Wood and plywood	0	0	Air Separation	0.85	0	0
☑ Aluminium	1	0.058				
☐ Copper	0	0	Eddy Current Separation	0.9	0.116	0.104
☑ Other Metals	1	0.058				
☑ Glass	14.2	0.843				
☐ Rubber	0	0	Heavy Medium Separation	0.75	1.076	0.807
☐ Concret and ceramics	0	0				
☑ Others	3.92	0.233				

Recalculate

Total Material Recovered: 5.571

Exit | Main Menu | << Step 4 | Step 6 >>

Figure 10.6: Composition and post fragmentation separation of the microwave oven

Product Evaluation Process ...

Step 06: Identify Safe Disposal for your Product

< Microwave >

Inefficiencies of the material separation processes and economics of available recycling technologies necessitate safe disposal of the shredder residue. Certain hazardous substances removed from WEEE also require safe disposal.

Weight of the Product to be disposed (kg) 1.379

Disposal suitable for landfill	Weight (kg)
☑ Controlled landfill of Skin floatation process waste	0.026
☑ Dispose the waste as MWS	0.044

Disposal suitable for Incineration	
☑ Controlled Incineration of Electrostatic seperation waste	0.165
☑ Incinerate Air separation process fluff	0
☑ Incinerate Heavy medium separation process fluff	0.172
☑ Controlled incincration of other hazardous materials	0.75

Important Notes:

Incineration of WEEE can result in high concentration of metals, heavy metals in the slag, the flue gas or the filter cakes. Care is to be taken to dispose certain materials included in the WEEE which are not suitable for incineration in view of the hazardous nature of the flue gas residues and are better to be sent to controlled landfill.

Exit | Main Menu | << Step 5 | Generate Recycling Process Plan

Figure 10.7: Safe disposal of the microwave oven

10.3.2 Legislative Compliance Monitoring

The second stage of the RPP framework identifies the legislative requirements related to the recycling of the microwave oven. The compliance to both the WEEE directive and RoHS directive is monitored within this stage. For the microwave oven compliance monitoring involves checking the scope of the relevant directives, definition of its relevant pre-treatment requirements, and the definition of the recovery and recycling targets. As mentioned, the microwave oven falls within the scope of WEEE directive in the large household appliances category. As far as the definition of the pre-treatment requirements for the microwave oven is concerned the removal of the external electric cable, magnetron and fluorescent lamp are identified as they are classified as hazardous under the hazardous waste directive.

As the microwave oven falls in the large household appliances category, WEEE directive requires 80% of its weight being recovered with at least 75% of its weight being recycled or reused. In the WEEE directive, these recycling targets are considered necessary to avoid the limitation of recovery to incinerate or removal of few valuable materials only, with the rest of the product going to disposal operations. In this context, the recycling is defined as the reprocessing in a production process of the waste materials for the original purpose or for other material reuse purposes but excluding energy recovery. Hence, in this case study the recycling rate achieved for the microwave oven is calculated based on the weight of the valuable materials and components removed for possible reuse and other recycling processes involving post fragmentation material recovery options. Similarly, the recovery rate achieved for the microwave oven is based on the weight recycled plus the weight processed through the recovery processes involving incineration (energy recovery).

10.3.3 Recycling Process Planning

In the third stage of the RPP framework, a bespoke recycling process plan is generated for the microwave oven. The generation of recycling process planning stage is demonstrated through the recycling process planning module of the CA*R*PP. The recycling process planning module uses the information from other modules (i.e. the user interface module and the database module) to generate a bespoke recycling process plan

for the microwave oven. The product evaluation information and the legislative compliance monitoring information described so far in this case study are used within the recycling process planning module to customise the standard recycling process plan for large household appliances into the bespoke recycling process plan for the microwave oven .

The five stage recycling process plan shown in Figure 10.8 provides a systematic process to recycle the microwave oven. The compliance monitor at the bottom right corner of the recycling process plan clearly highlights that both the recovery and recycling targets will be easily met by following the sequence of recovery and recycling processes included in the recycling process plan (see Figure 10.8). In the next stage of the RPP framework, ecological and economical impacts associated with this bespoke recycling process plan are calculated and are compared with the overall performance under other end-of-life options.

10.3.4 Ecological and Economical Assessment

In the final stage of the RPP framework the ecological and economical impacts of various end-of-life options for the microwave oven are analysed. The Eco^2 assessment stage is demonstrated through the assessment module of the CA*R*PP. Different tasks included in the Eco^2 assessment are described in the following sections.

10.3.4.1 Material Composition of the Microwave Oven

Material composition of the microwave oven is identified during the product evaluation stage. The microwave oven mainly consists of ferrous metals (65.4%), plastics (8%), copper (11%), glass (7.8%) and mixture of other materials (7.8%) (without removing hazardous, valuable and penalty materials from the product).

10.3.4.2 Different End-of-Life Options for the Microwave Oven

In the assessment module the following three end-of-life options have been selected for detailed ecological and economical assessment.

Recycling Process Plan...

Step 07: Recycling Process Plan for your Product

The Recycling process plan for: < Microwave >

Recycle Product Name:	Microwave
Recycle Product Category:	Large household appliances
Net Product Weight:	11.4
Total Hazardous Material Weight(kg):	1.05
Weight Sent to Shredder(kg):	6.2
Weight disposed as MWS(kg):	0.170

Process ID | Process Description | Weight Processed

OP100 Depollution for legistlative compliance:

Sub-Op104	Remove Fluorescent lamp for controlled Incineration	0.1
Sub-Op109	Remove External electric cable for Material Recovery	0.2
Sub-Op113	Remove Magnetron for controlled Incineration	0.75

OP200 Valuable parts recovery:

Sub-Op207	Remove Motor for Material Recovery	0.3
Sub-Op211	Remove Transformer for Material Recovery	3.6
Sub-Op213	Remove Tray Motor for Material Recovery	0.1

Weight of the Product Recycled	9.555
Weight of the Product Recovered	9.902

Process ID | Process Description | Weight Processed

OP300 Dismantling to remove Penalty substances:

Sub-Op306	Remove Cables for Material Recovery	0.15

OP400 Shredding and Mechanical Separation:

Sub-Op402	Use Air Separation to recover lighter fractions	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	4.107
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.109
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.830
Sub-Op409	Use Skin Floatation to recover FR plastics	0.084
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.425

OP500 Safe Disposal:

Sub-Op501	Incinerate Air separation process fluff	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.177
Sub-Op503	Controlled incincration of other hazardous materials	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.026
Sub-Op508	Dispose the waste as MWS	0.044
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.170

Compliance Monitor

Microwave	Recovery (%)	Recycling (%)
Targets	80	75
Achieved	86.86	83.82
Compliance	Yes	Yes

Exit | Save Recycling Process Plan | ECO2 Assessment >>

Figure 10.8: Bespoke recycling process plan for the microwave oven

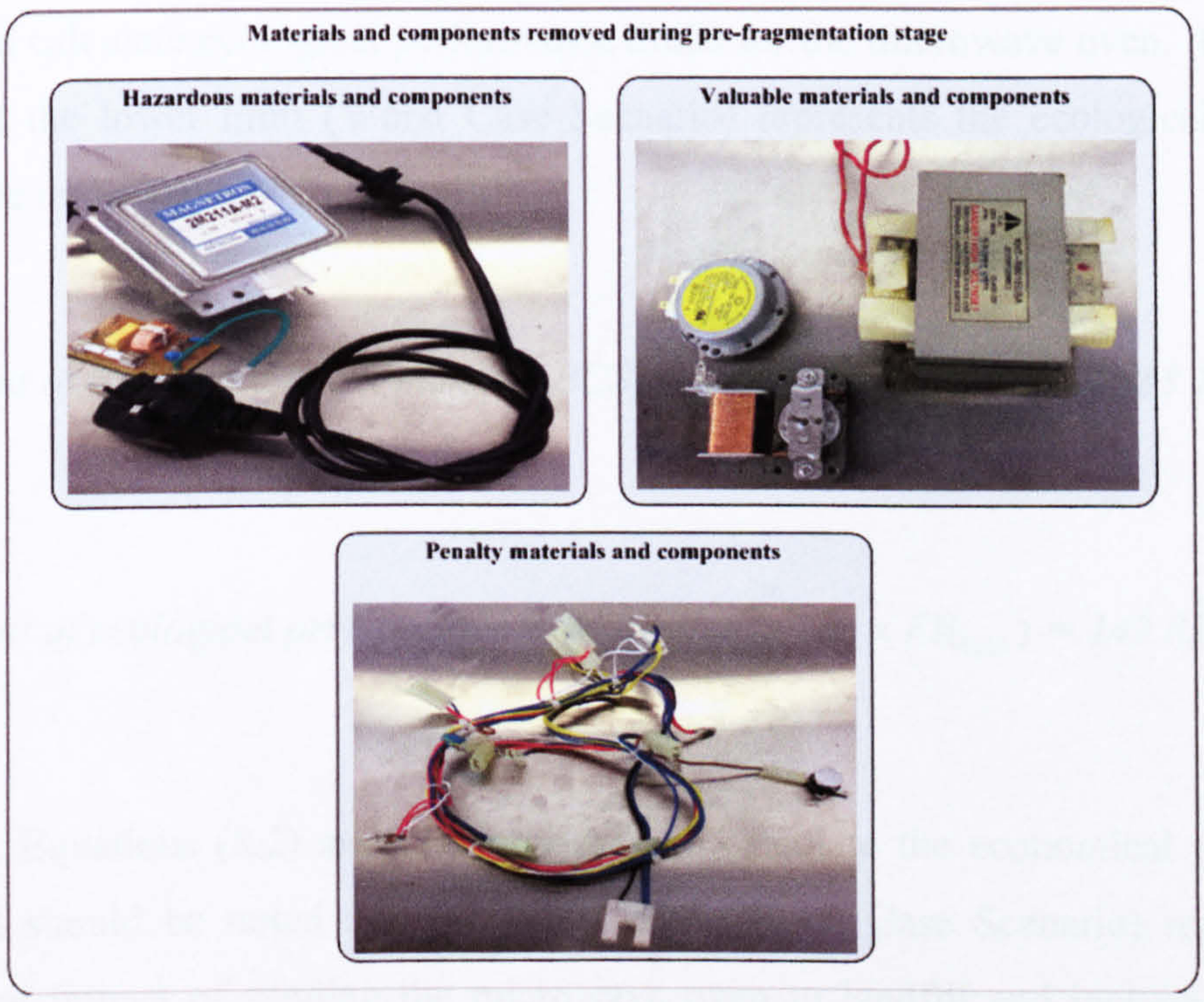


Figure 10.9: Materials and components dismantled from the microwave oven

i. *Recycling through shredding after depollution*: This option involves using a fragmentation process like shredding to break the depolluted microwave oven into small fractions. Subsequently, different mechanical separation processes are used to recover different materials within the shredded product. This option is often used within the current recovery and recycling facilities.

ii. *Recycling through recycling process plan*: This option involves recycling of the microwave oven through the novel five stage recycling process plan shown in Figure 10.8.

iii. *Landfilling:* This option involves disposal of the microwave oven to the landfill.

10.3.4.3 Calculation of the Performance Limits

Based on the material composition of the microwave oven, an upper limit and a lower limit of ecological and economical performance are calculated. The actual performance of the microwave oven in different end-of-life options will be evaluated with reference to these performance limits in the later stages of the Eco^2 assessment. Figure 10.10 and 10.11 highlights the calculation of the ecological and economical performance limits for the microwave oven through the CA*R*PP. Equations (8.1) and (8.3) (see section 8.4.3) are used to calculate ecological performance limits for the microwave oven. It should be noted that the lower limit (Worst Case Scenario) represents the ecological impact of sending the microwave oven to landfill.

$$\textit{Upper limit of ecological performance} = BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) = -2888.1mPt$$

$$\textit{Lower limit of ecological performance} = WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) = 142.03mPt$$

Similarly, Equations (8.2) and (8.4) are used to calculate the economical performance limits. It should be noted that the lower limit (Worst Case Scenario) represents the economical impact of sending the microwave oven to landfill and include the cost of depollution.

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Microwave >

Upper and Lower Limits of Environmental Performance for < Microwave >

Recycle Product Name: < Microwave > Net Product Weight: 11.4

An upper and lower limit of end-of-life Environmental Performance is calculated to evaluate the environmental performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg)		mi x Eli bcs (mPt)	mi x Eli wcs (mPt)
		Material Substitution (Eli bcs)	Landfill (Eli wcs)		
Steel	7.46	-86	1.4	-641.56	10.44
FR Plastics	0	-383.3	3.95	0	0
NFR Plastics	0.91	-383.3	3.95	-348.8	3.59
Wood / Plywood	0	-39	4.2	0	0
Aluminium	0	-780	1.4	0	0
Copper	1.25	-1400	1.4	-1750	1.75
Other metals	0	-1150.9	1.4	0	0
Glass	0.89	-66	1.4	-58.74	1.25
Rubber	0	-360	7.4	0	0
Concrete	0	-3.8	1.4	0	0
Others	0.89	-100	1.4	-89	1.25

Upper limit of Ecological Performance = -2888.1

Lower limit of Ecological Performance = 142.03

Upper limit of environmental performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any environmental burden of treatment processes."

Lower limit of environmental performance is calaculated considering that every material in the Product is ending up in the landfill without any environmental burden of treatment processes."

Exit | Recycling Process Plan | Step 2 >>

Figure 10.10: Calculation of the ecological performance limits

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Microwave >

Upper and Lower Limits of Economical Performance for < Microwave >

Recycle Product Name: < Microwave > Net Product Weight: 11.4

An upper and lower limit of end-of-life Economical Performance is calculated to evaluate the economical performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg)		mi x Cli bcs (£)	mi x Cli wcs (£)
		Material Revenue (Cli bcs)	Disposal Cost (Cli wcs)		
Steel	7.46	0.07	0.03	0.52	0.22
FR Plastics	0	0.1	0.03	0	0
NFR Plastics	0.91	0.1	0.05	0.09	0.05
Wood / Plywood	0	0	0.03	0	0
Aluminium	0	0.8	0.03	0	0
Copper	1.25	2.8	0.03	3.5	0.04
Other metals	0	0.1	0.03	0	0
Glass	0.89	0.03	0.04	0.03	0.04
Rubber	0	0.1	0.03	0	0
Concrete	0	0	0.03	0	0
Others	0.89	0	0.08	0	0.07

Upper limit of Economical Performance = -4.14

Lower limit of Economical Performance = 2.92

Cost of Depollution = 2.5

Upper limit of economical performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any economical burden of treatment processes."

Lower limit of economical performance is calaculated considering that every material in the Product is ending up in the landfill."

Exit | Recycling Process Plan | Step 2 >>

Figure 10.11: Calculation of the economical performance limits

$$\textit{Upper limit of economical performance} = BCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{BCS}) = \text{- £4.14}$$

$$\textit{Lower limit of economical performance} = WCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{WCS}) = £2.92.$$

10.3.4.4 Calculation of the Actual Performance of Different End-of-Life Options

Different end-of-life options considered for recycling of the microwave oven includes recycling through shredding after depollution, recycling through recycling process plan, and landfilling. The calculation of the actual performance of shredding option within the assessment module of the CA***R***PP is illustrated in Figure 10.12 and 10.13. The assessment module retrieves the relevant data from the other modules of the CA***R***PP (see section 9.7.4). Equations (8.5) and (8.6) (see section 8.4.4) are used within the assessment module to calculate the actual ecological and economical performance of the product through shredding option.

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Microwave >

Environmental Impact Assessment of the current recycling practice for < Microwave >

Recycle Product Name: < Microwave > Hazardous Materials Weight: 1.05 Shredding Weight: 10.35

End-of-life environmental performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) (Eli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
		Material Substitution	Landfill	Incineration			
Steel	6.77	-86	-	-	0.95	0.8	-442.49
FR Plastics	0	-	3.95	-	1	1	0
NFR Plastics	0.83	-383.3	-	-	0.70	0.6	-133.62
Wood / Plywood	0	-	-	-12	1	1	0
Aluminium	0	-780	-	-	0.85	0.65	0
Copper	1.14	-1400	-	-	0.85	0.7	-949.62
Other metals	0	-	-	-32	1	1	0
Glass	0.81	-	1.4	-	1	1	1.13
Rubber	0	-	7.4	-	1	1	0
Concrete	0	-	1.4	-	1	1	0
Others	0.81	-	1.4	-	1	1	1.13
			Actual Ecological Performance		=	-1411.6	

Exit | Recycling Process Plan | Step 3 >>

Figure 10.12: Calculation of actual ecological performance through shredding after depollution option

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Microwave >

Economical Impact Assessment of the current recycling practice for < Microwave >

Recycle Product Name: < Microwave > Hazardous Materials Weight: 1.05 Shredding Weight: 10.35

End-of-life economical performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)			Process Efficiency (PEi)	Grade (G)	mi x Cli ap x PEi x Gi (£)
		Processing Cost	Disposal Cost	Material Revenue			
Steel	6.77	0.02	-	0.07	0.95	0.8	-0.26
FR Plastics	0	0.025	0.015	-	1	1	0
NFR Plastics	0.83	0.025	-	0.1	0.70	0.6	-0.03
Wood / Plywood	0	0.018	0.015	-	1	1	0
Aluminium	0	0.028	-	0.8	0.85	0.65	0
Copper	1.14	0.030	-	2.8	0.85	0.7	-1.88
Other metals	0	0.030	0.015	-	1	1	0
Glass	0.81	0.024	0.04	-	1	1	0.05
Rubber	0	0.024	0.015	-	1	1	0
Concrete	0	0.015	0.015	-	1	1	0
Others	0.81	0.015	0.08	-	1	1	0.08

Actual Economical Performance = -2.04

Cost of Depollution = 2.5

Exit | Recycling Process Plan | Step 3 >>

Figure 10.13: Calculation of actual economical performance through shredding after depollution option

Actual ecological performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -1411.6mPt$$

Actual economical performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £0.46$$

The calculation of the actual performance of the recycling process plan option is illustrated in Figure 10.14 and 10.15. Based on the end-of-life destination of each material or component, an ecological impact value and various end-of-life costs are assigned to individual processes contained in the recycling process plan for the microwave oven. Equations (8.5) and (8.6) are used within the assessment module to calculate the actual ecological and economical performance for the microwave oven through the recycling process plan option.

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Microwave >

Environmental Impact Assessment of the Proposed Recycling Process Plan for < Microwave >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Environmental Impact (mPt/kg) (Eli ap)				Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
			Material Substitution	Landfill	Incineration	Actual		
Sub-Op104	Remove Fluorescent lamp for controlled Incineration	0.1	-	-	-20.7	-20.7	1	-2.07
Sub-Op109	Remove External electric cable for Material Recovery	0.2	-891.6	2.67	-82.7	-891.6	0.75	-133.74
Sub-Op113	Remove Magnetron for controlled Incineration	0.75	-395.1	7.83	-20.7	-20.7	1	-15.52

Valuable Recovery

Sub-Op207	Remove Motor for Material Recovery	0.3	-611.6	1.96	-	-611.6	0.8	-146.78
Sub-Op211	Remove Transformer for Material Recovery	3.6	-471.6	1.98	-	-471.6	0.8	-1358.21
Sub-Op213	Remove Tray Motor for Material Recovery	0.1	-550	1.95	-	-550	0.75	-41.25

Penalty Removal

Sub-Op306	Remove Cables for Material Recovery	0.15	-1079	2.15	-	-1079	0.75	-121.39

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-39	4.2	-12	-12	0.75	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	4.107	-86	1.4	-32	-86	0.8	-282.56
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.109	-1105.9	1.4	-110	-1150.9	0.65	-81.54
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.830	-89.4	2.4	6.9	-89.4	0.6	-44.52
Sub-Op409	Use Skin Floatation to recover FR plastics	0.084	-383.4	3.95	37	3.85	0.6	0.19
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.425	-383.4	3.95	-13	-383.3	0.6	-97.74

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	4.2	-12	-12	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.177	-	2.4	6.9	6.9	1	1.22
Sub-Op503	Controlled incincration of other hazardous materials	0	-	7.83	-20.8	-20.8	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.026	-	3.95	37	3.95	1	0.1
Sub-Op508	Dispose the waste as MWS	0.044	-	1.4	-15	-15	1	-0.66
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.170	-	3.95	-13	-13	1	-2.21

Actual Ecological Performance = -2326.68

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure 10.14: Calculation of actual ecological performance of recycling through recycling process plan

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Microwave >

Economical Impact Assessment of the Proposed Recycling Process Plan for < Microwave >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)				Grade (Gi)	mi x Cli ap x PEi x Gi (£)
			Disassembly Cost	Processing Cost	Disposal Cost	Material Revenue		
Sub-Op104	Remove Fluorescent lamp for controlled Incineration	0.1	0.5	-	0.025	-	-	0.5
Sub-Op109	Remove External electric cable for Material Recovery	0.2	0.4	0.015	-	1.1	0.75	0.24
Sub-Op113	Remove Magnetron for controlled Incineration	0.75	1.6	-	0.025	-	1	1.62

Valuable Recovery

Sub-Op207	Remove Motor for Material Recovery	0.3	0.4	0.015	-	1.75	0.8	-0.02
Sub-Op211	Remove Transformer for Material Recovery	3.6	0.5	0.015	-	1.64	0.8	-4.18
Sub-Op213	Remove Tray Motor for Material Recovery	0.1	1	0.015	-	0.75	0.75	0.94

Penalty Removal

Sub-Op306	Remove Cables for Material Recovery	0.15	0.1	0.015	-	1.1	0.75	-0.02

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-	0.018	0.015	0	1	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	4.107	-	0.02	0	0.07	0.8	-0.16
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.109	-	0.03	0	1.99	0.65	-0.14
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.830	-	0.025	0.015	0	1	0.03
Sub-Op409	Use Skin Floatation to recover FR plastics	0.084	-	0.025	0.015	0	1	0
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.425	-	0.025	0	0.1	0.6	-0.02

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	0.018	0.015	0	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.177	-	0.025	0.015	0	1	0.01
Sub-Op503	Controlled incincration of other hazardous materials	0	-	0.015	0.025	0	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.026	-	0.025	0.015	0	1	0
Sub-Op508	Dispose the waste as MWS	0.044	-	0.025	0.015	0	1	0
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.170	-	0.025	0.015	0	1	0.01

Actual Economical Performance = -1.19

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure 10.15: Calculation of actual economical performance of recycling through recycling process plan

Actual ecological performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -2326.7mPt$$

Actual economical performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = -£1.19$$

10.3.4.5 Comparison of the Performance of Different End-of-Life Options

The actual ecological and economical performances of different end-of-life options for the microwave oven are compared with the respective performance limits in order to evaluate theses end-of-life options. The comparison of the ecological and economical performances within the assessment module of the CA*R*PP is illustrated in Figure 10.16. The comparison shows that the recycling of the microwave oven through recycling process plan option results in better ecological as well as economical performance than shredding and landfilling options.

10.3.4.6 Generation of the Combined Ratios for Ranking Different End-of-Life Options

Finally, the combined Eco^2 performance ratios of different end-of-life options providing an overview of their ecological and economical performances are calculated. For the microwave, the calculation of EPR_{ecol} and EPR_{econ} and finally C*E*PR for different end-of-life options is outlined below.

The upper and lower performance limits for the microwave are calculated in section 10.3.4.3 and are:

- Upper ecological performance limit BCS_{ecol} = -2881.1 mPt
- Lower ecological performance limit WCS_{ecol} = 142.03 mPt
- Upper economical performance limit BCS_{econ} = -£4.14
- Lower economical performance limit WCS_{econ} = £2.92

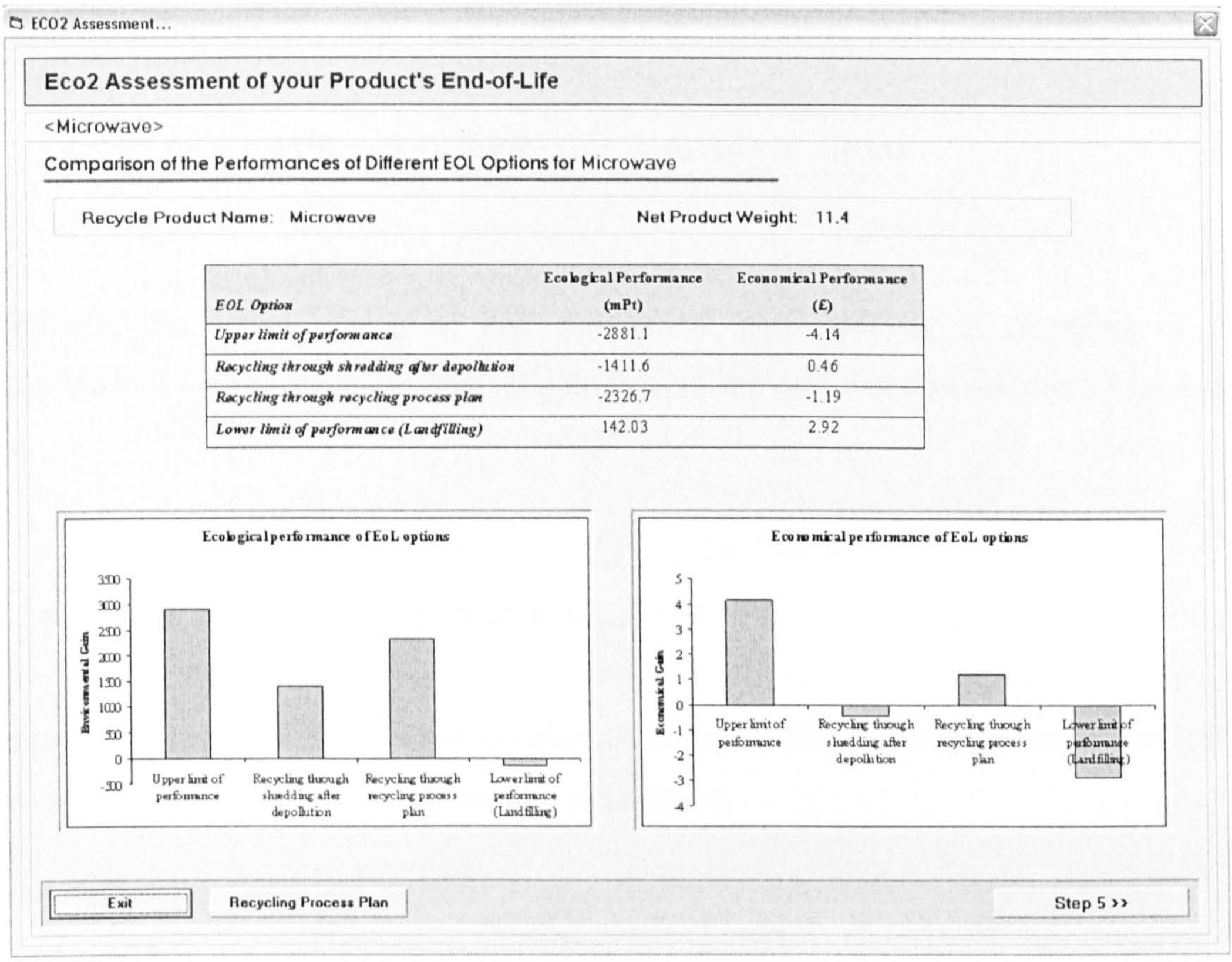


Figure10.16: Comparison of performances of different end-of-life options for the microwave oven

The actual ecological and economical performances of recycling of the microwave through 'shredding after depollution' are calculated in section 10.3.4.4 and are:

- Actual ecological performance AP_{ecol} = -1411.6 mPt
- Actual economical performance AP_{econ} = £0.46

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for shredding after depollution.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-1411.6 - 142.03}{-2881.1 - 142.03} = 0.514$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{0.46 - 2.92}{-4.14 - 2.92} = 0.348$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.514 + 0.348}{2} = 0.431$$

Similarly, the actual ecological and economical performances of recycling of the microwave through 'recycling process plan option' are calculated in section 10.3.4.4 and are:

- Actual ecological performance AP_{ecol} = -2326.7 mPt
- Actual economical performance AP_{econ} = -£1.19

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for recycling process plan option.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-2326.7 - 142.03}{-2881.1 - 142.03} = 0.816$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{-1.19 - 2.92}{-4.14 - 2.92} = 0.582$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.816 + 0.582}{2} = 0.699$$

The ecological and economical performance ratios along with the combined performance ratio of different end-of-life options for the microwave are summarised in Table 10.1. As C*E*PR ranges from '0' to '1', with '0' being the lower performance limit (worst case scenario) and '1' being the upper performance limit (best case scenario) (see section 8.4.6 for these calculations), the higher value of C*E*PR (close to 1) represents a good overall performance of the assessed end-of-life option. Hence, it can be concluded that the overall performance of the recycling process plan option (C*E*PR = 0.699) is better than the shredding after depollution option (C*E*PR = 0.431).

EoL Option	Ecological Performance Ratio (EPR_{ecol})	Economical Performance Ration (ERP_{econ})	Combined Eco^2 Performance Ratio (*CE*PR)
Upper limit of performance	1	1	**1**
Shredding after depollution option	0.514	0.348	**0.431**
Recycling process plan option	0.816	0.582	**0.699**
Lower limit of performance	0	0	**0**

Table 10.1: Performance ratios for different end-of-life options for the microwave oven

Figure 10.17 depicts the ranking of different end-of-life options for the microwave in relation to the best and worst case scenario, clearly showing that the recycling process planning option is the best recycling route. This underlines the substantial improvements achieved in the environmental and economical performance through adoption of a systematical approach for generation of a recycling process plan based on the most up-to-date information and knowledge on recycling processes, contained within the CA***R***PP.

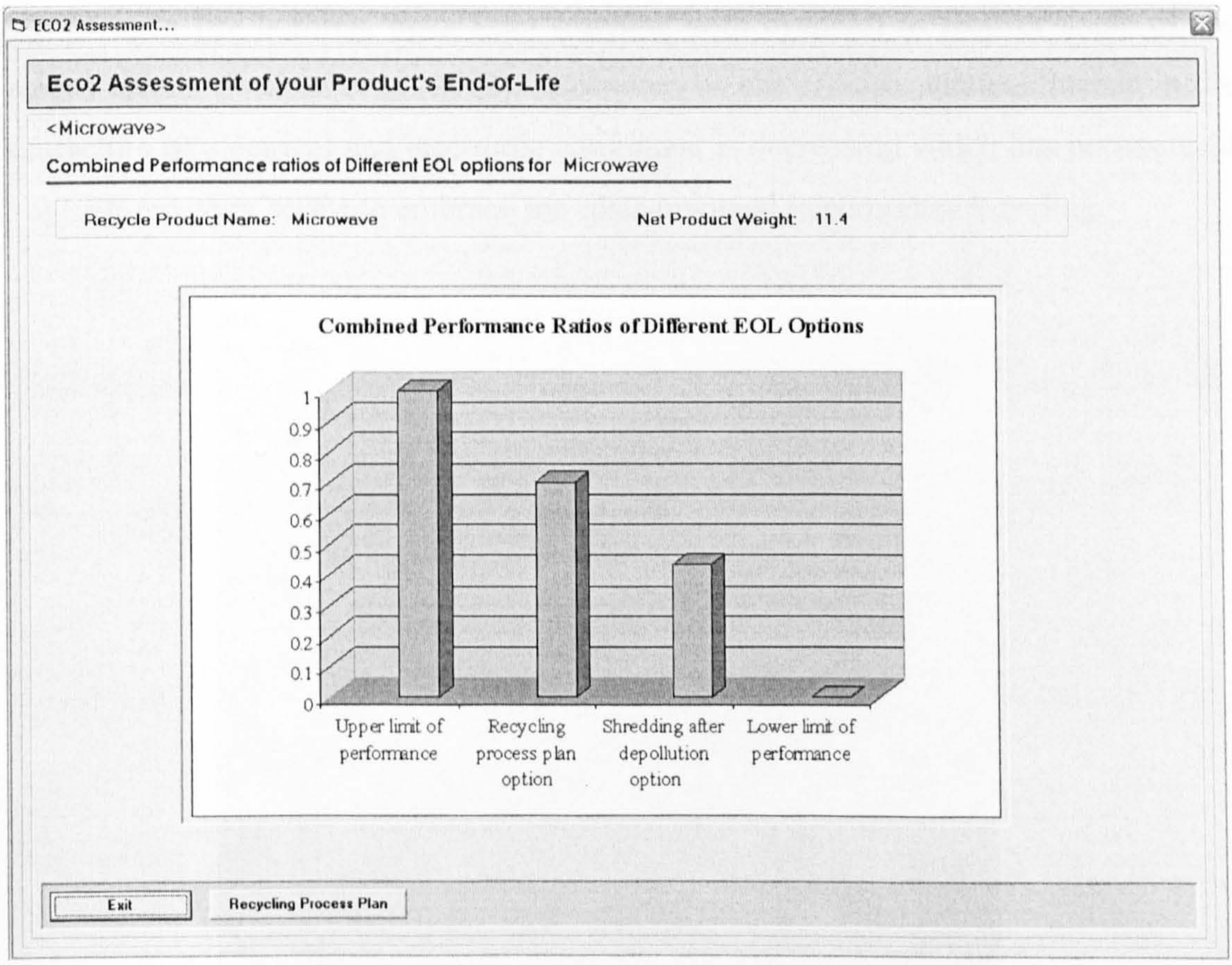


Figure 10.17: Overall ranking of different end-of-life options for the microwave oven

10.4 Case Study 2: Desktop Computer

The product considered for the second case study is a desktop computer (see Figure 10.18) which is classified as 'IT and telecommunication equipment' category in WEEE Directive. Nearly all desktop computers are modular, with components that can easily be replaced or upgraded. However, low prices together with rapid technological changes mean that there are always better and more powerful products on the market which have encouraged consumers to frequently replace their computers. The result is a burgeoning computer waste mountain.

Discarded computer equipment typically comprises of monitors, printers, keyboards, hard drives, processors and circuit boards, etc. Such items must not be thrown out with household rubbish due to its hazardous substance content, and the original manufacturers are obliged to meet the recovery and recycling targets within the WEEE directive. The current recycling practice is based on exporting the desktop computers to developing countries, where they are treated under inappropriate conditions in backyard operations (such as open fire burning, open heap leaching with cyanide) to recover some of the precious metals (Puckett *et al.* 2002). However, as use of such precious metals in the manufacture of electrical and electronic equipment is decreasing which has necessitated the WEEE recovery sector to embrace the costs involved in computer recycling.

Figure 10.18: Case study 2: Desktop computer

The RPP framework established in this research aims to reduce these costs by improved value recovery as well as improve the environmental performance of computer recycling. It should be noted that the process of conducting the second case study is identical to the first case study which follows the various stages in the RPP framework. The full implementation of the RPP framework through associated CA***R***PP for the recycling of computer is illustrated in *Appendix 5*.

10.4.1 Product Evaluation

The first stage of the RPP framework, namely the product evaluation, is used to identify the main characteristics and material composition information of the computer which can then be used by other modules of the CA***R***PP in order to generate the bespoke recycling process plan. The identification of the product and its category in the first task of the product evaluation establishes the WEEE directive's recovery and recycling targets together with the average weight for the computer (Figure 10.19). The indicative weight assigned to the computer (and its monitor) (i.e. 35kg) is changed to the exact weight of the computer under consideration (i.e. 37.75 kg).

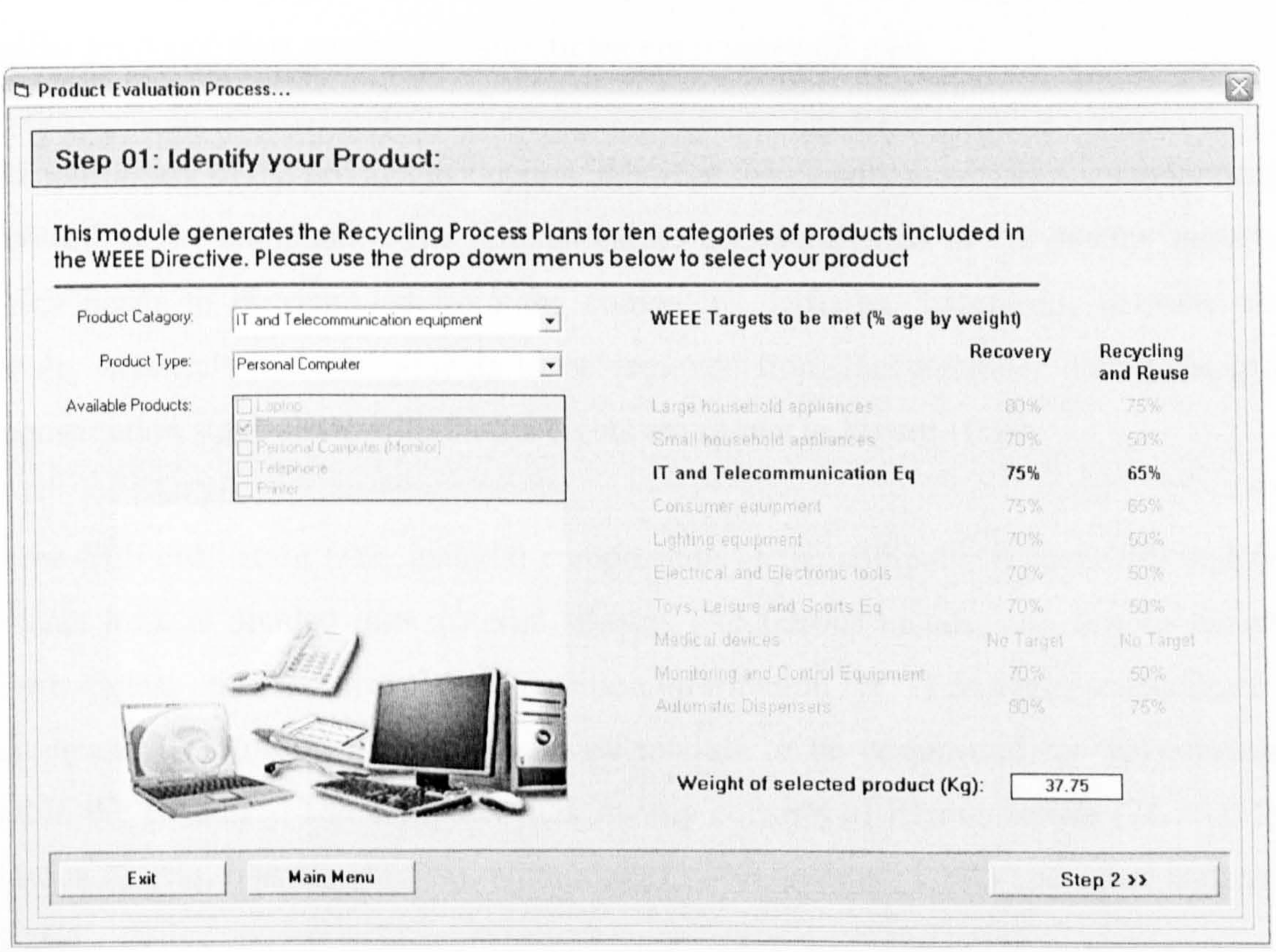


Figure 10.19: Identification of the case study product and its WEEE category

The second task in the product evaluation identifies the hazardous materials and components included in the computer. External electric cable and battery are highlighted along with their indicative weights as the hazardous components which need to be removed from the computer in order to comply with the pre-treatment requirements of the WEEE directive. In case of the computer, another component namely the mother board is considered hazardous in nature. The motherboard is rich with chemicals like chromium, cadmium, flame retardant, mercury, lead, polyvinyl chloride coating on cables and nickel in batteries. Its disposal to landfill involves disastrous environmental and health problems. Yet, it is possible to recover the precious metals from the properly depopulated board via smelting.

The third evaluation task identifies the valuable materials and components present in the computer. Different valuable materials and components highlighted within this evaluation task included processor, network card, memory, power supply, hard disk drive and CD drive. As mentioned, such pre-fragmentation removal of the valuable materials improves the ecological and economical performance of product recycling. These valuable components can be reused in repair and remanufacturing environments for similar products, thus resulting in significant environmental gain.

The fourth task in the product evaluation identifies the penalty materials and components included in the computer. The internal cables are highlighted as the penalty material which needs to be removed from the computer. Different hazardous, valuable and penalty materials and components to be removed from the computer during the pre-fragmentation stage along with their weights are shown in Figure 10.20.

In the fifth evaluation task, material composition of the computer is identified and the product hulk is divided into material streams like ferrous metals, non ferrous metals, plastics, glass etc. The material composition information for 'IT and telecommunication equipment' is retrieved from the database module to be customised for the computer within the CA*R*PP. The computer hulk mainly consists of ferrous metals (78.2%), FR plastics (2.2%), plastics (11.7%), aluminium (3.6%), copper (1.1%) and other materials (3.2%).

Figure 10.20: Materials and components dismantled from the computer

Based on this material composition appropriate shredding and mechanical separation processes are assigned to the product hulk. The final task in the product evaluation identifies the safe disposal processes to be used for the computer.

10.4.2 Legislative Compliance Monitoring

The second stage of the RPP framework is used to identify the WEEE requirements related to the end-of-life management of the computer. This compliance monitoring involves checking firstly the scope of the directives, secondly the pre-treatment requirements and finally the recovery and recycling targets with respect to the computer.

The computer falls within the scope of the WEEE directive in the 'IT and telecommunication equipment' category. Specific pre-treatment requirements for the monitor (containing cathode ray tube), brominated flame retarded plastics, printed circuit boards and batteries included in the computer are required to be met under the WEEE directive. As a minimum, these hazardous materials and components needs to removed from the computer before the fragmentation of the product. For the cathode ray tube, panel glass has to be separated from the funnel glass (leaded) and the fluorescent coating has to be removed. As far as recovery and recycling targets for the computer are concerned, WEEE directive requires 75% of its weight being recovered with at least 65% of its weight being recycled or reused.

10.4.3 Recycling Process Planning

The product evaluation information and the legislative compliance monitoring information are used within the recycling process planning module to customise the standard recycling process plan for 'IT and telecommunication equipment' into the bespoke recycling process plan for the computer. The complexity involved in the recovery and recycling of different materials and components included in the computer is managed through the application of the five stage recycling process plan developed in this stage. Figure 10.21 depicts the bespoke recycling process plan for the computer.

10.4.4 Ecological and Economical Assessment

In the final stage of the RPP framework the ecological and economical impacts associated with the recycling of the computer through recycling process plan option are calculated and compared with the impacts under current shredding practice and landfill options. The Eco^2 assessment methodology described in chapter 8 is used to calculate these ecological and economical impacts associated with computer recycling. The tasks involved in the calculation of the ecological and economical impacts are described in *Appendix 5*.

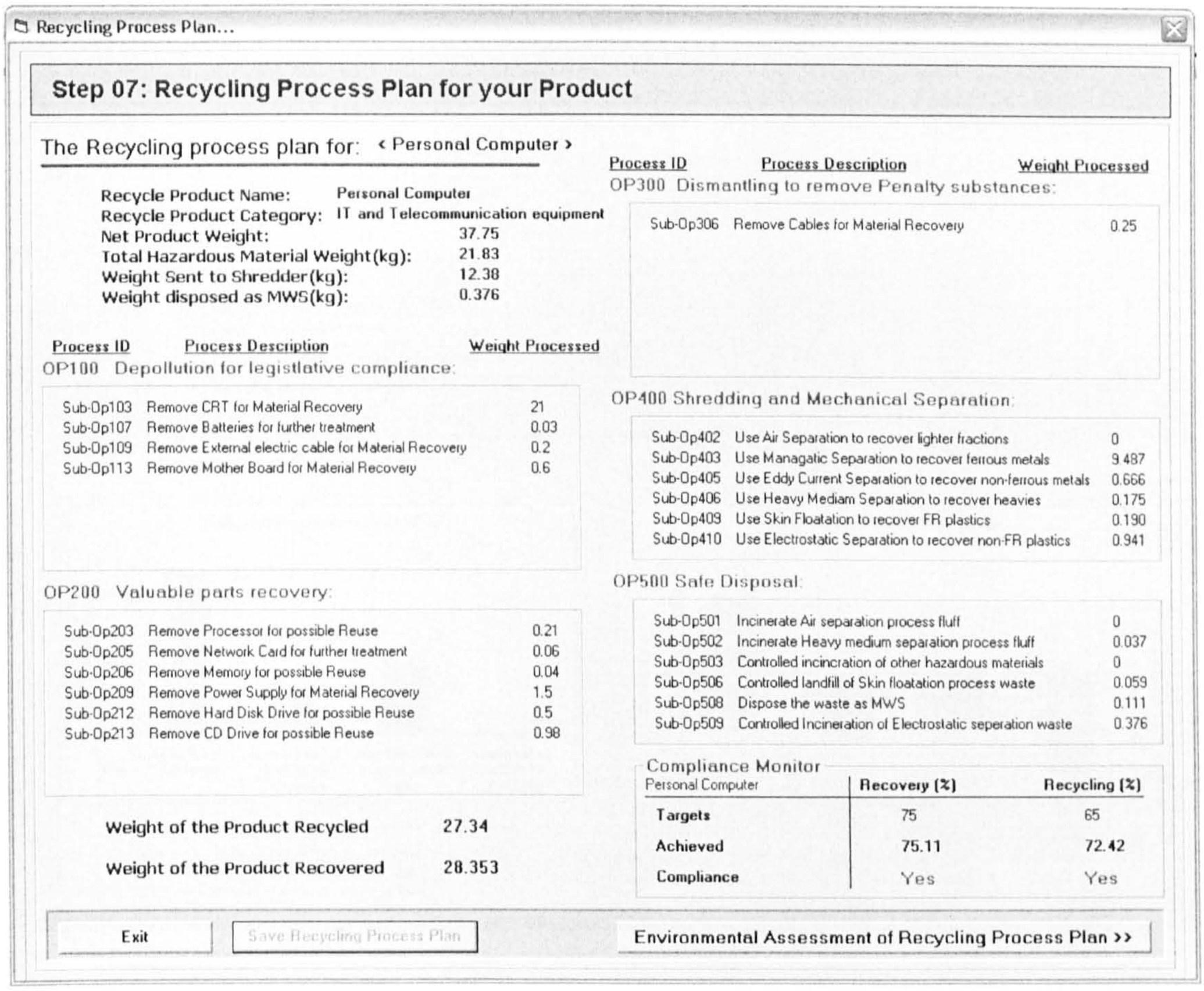


Figure 10.21: Bespoke recycling process plan for the computer

The comparison of the ecological and economical performances of different end-of-life options for computer within the assessment module of the CA***R***PP is illustrated in Figure 10.22. The comparison shows that the recycling of the computer through recycling process plan option is the best compromise solution than shredding and landfilling options.

Finally, the ecological and economical performance ratios along with the combined performance ratio of different end-of-life options for the computer are summarised in Table 10.2. It should be noted that the calculation of EPR_{ecol} and EPR_{econ} and finally C***E***PR for different end-of-life options for the computer is undertaken in the same way as described in the previous case study and is based on the approach described in section 8.4.6.

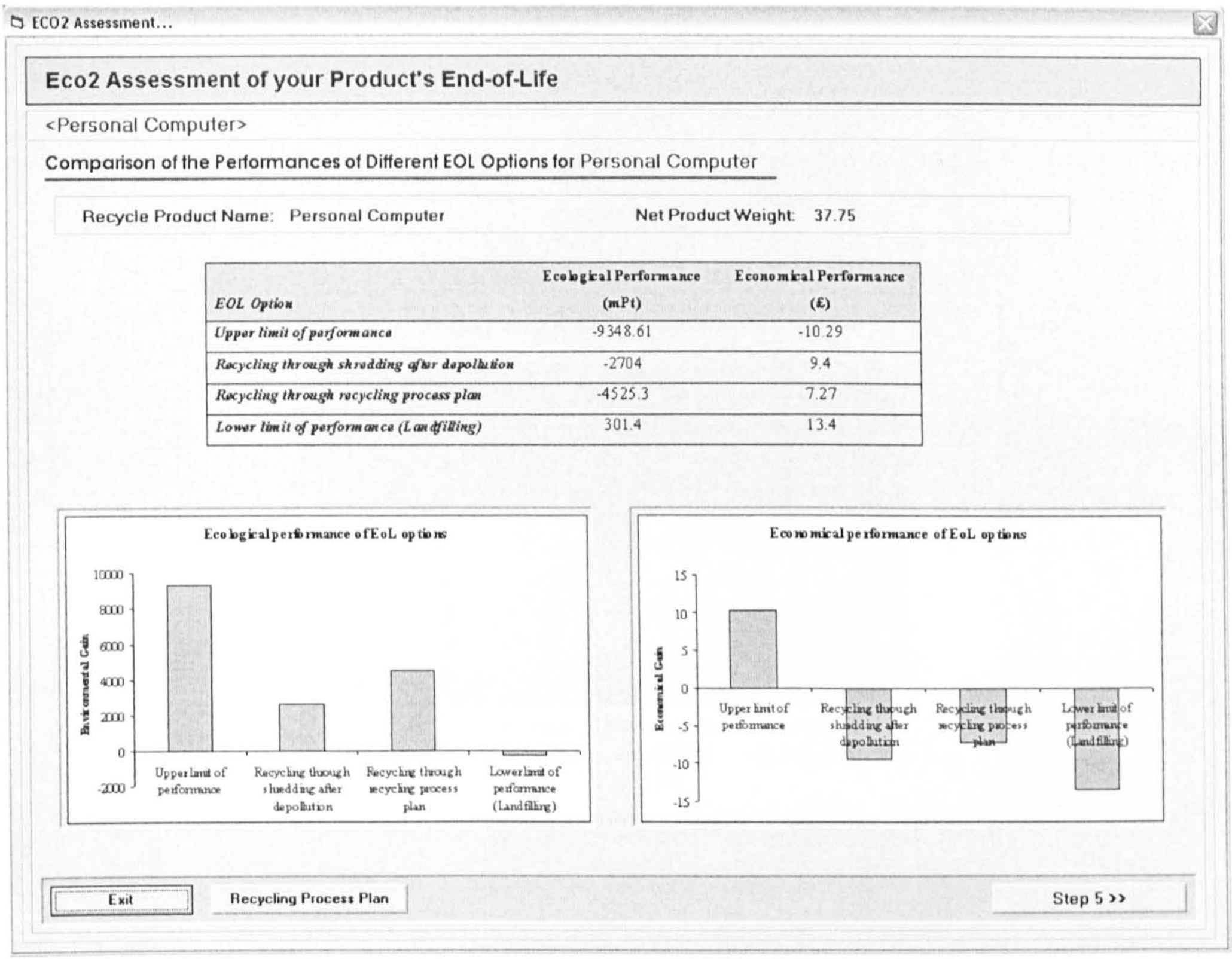


Figure10.22: Comparison of performances of different end-of-life options for the computer

As the higher value of C*E*PR (close to 1) represents a good overall performance of the assessed end-of-life option, it can be concluded that the overall performance of the recycling process plan option (C*E*PR = 0.38) is better than the shredding after depollution option (C*E*PR = 0.241) for the computer as depicted in Figure 10.23.

EoL Option	**Ecological Performance Ratio (EPR_{ecol})**	**Economical Performance Ration (ERP_{econ})**	**Combined Eco^2 Performance Ratio (C*E*PR)**
Upper limit of performance	1	1	**1**
Shredding after depollution option	0.312	0.17	**0.241**
Recycling process plan option	0.501	0.26	**0.38**
Lower limit of performance	0	0	**0**

Table 10.2: Performance ratios for different end-of-life options for the computer

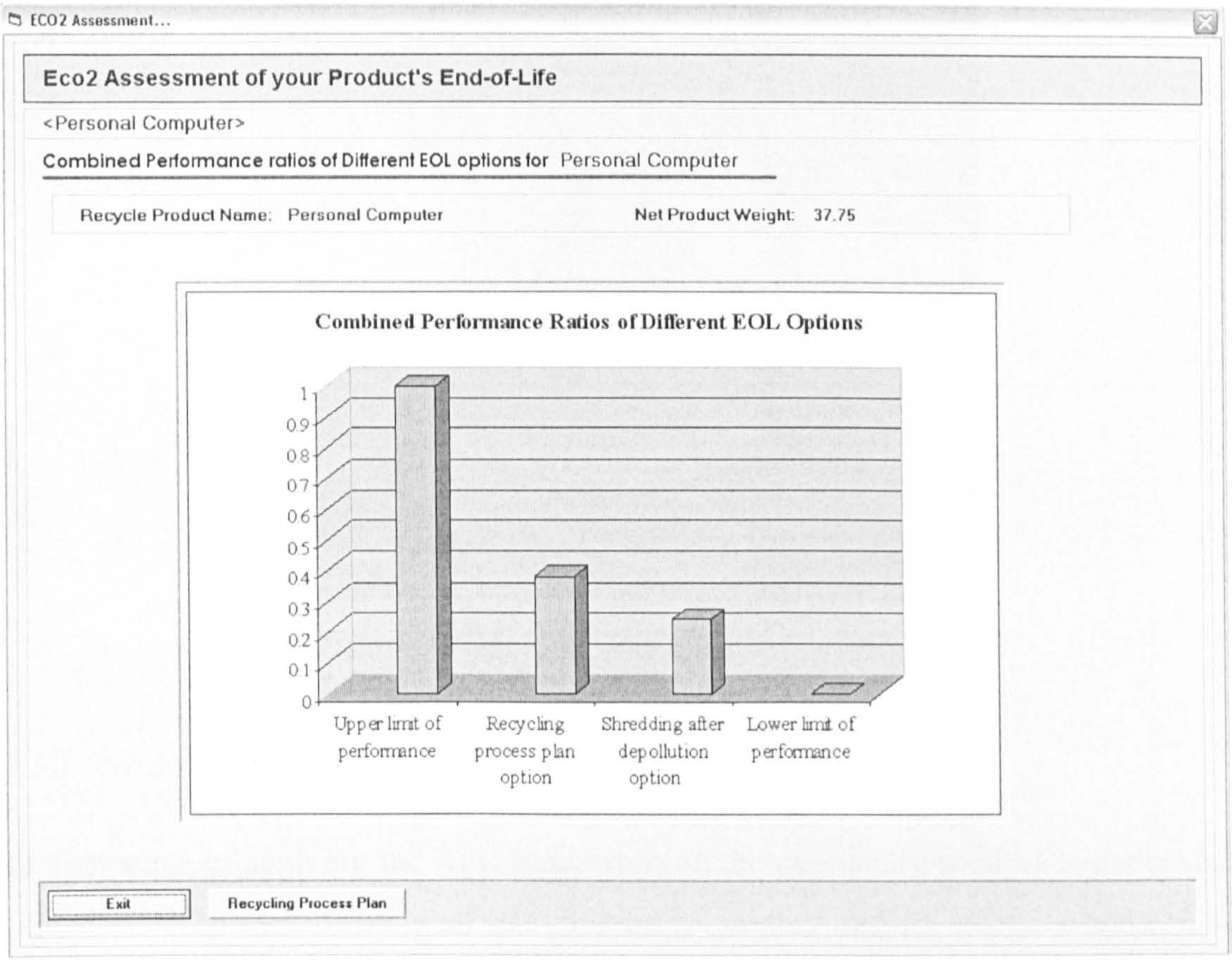


Figure 10.23: Overall ranking of different end-of-life options for the computer

10.5 Case Study 3: Electric Kettle

The third case study product is a typical electric kettle. The kettle used for this case study is a typical plastic cordless jug kettle (see Figure 10.24) consisting of a plastic base connected to the main power outlet, a detachable plastic jug, heating element and a thermostat. The electric kettle belongs to 'Small Household Appliance' category of WEEE. Small household appliances are usually disposed with household waste. In the wake of the current WEEE directive, the manufacturers are now responsible for recovery and recycling of the small household appliances. In the following sections, the RPP framework developed in this research is applied to this case study product.

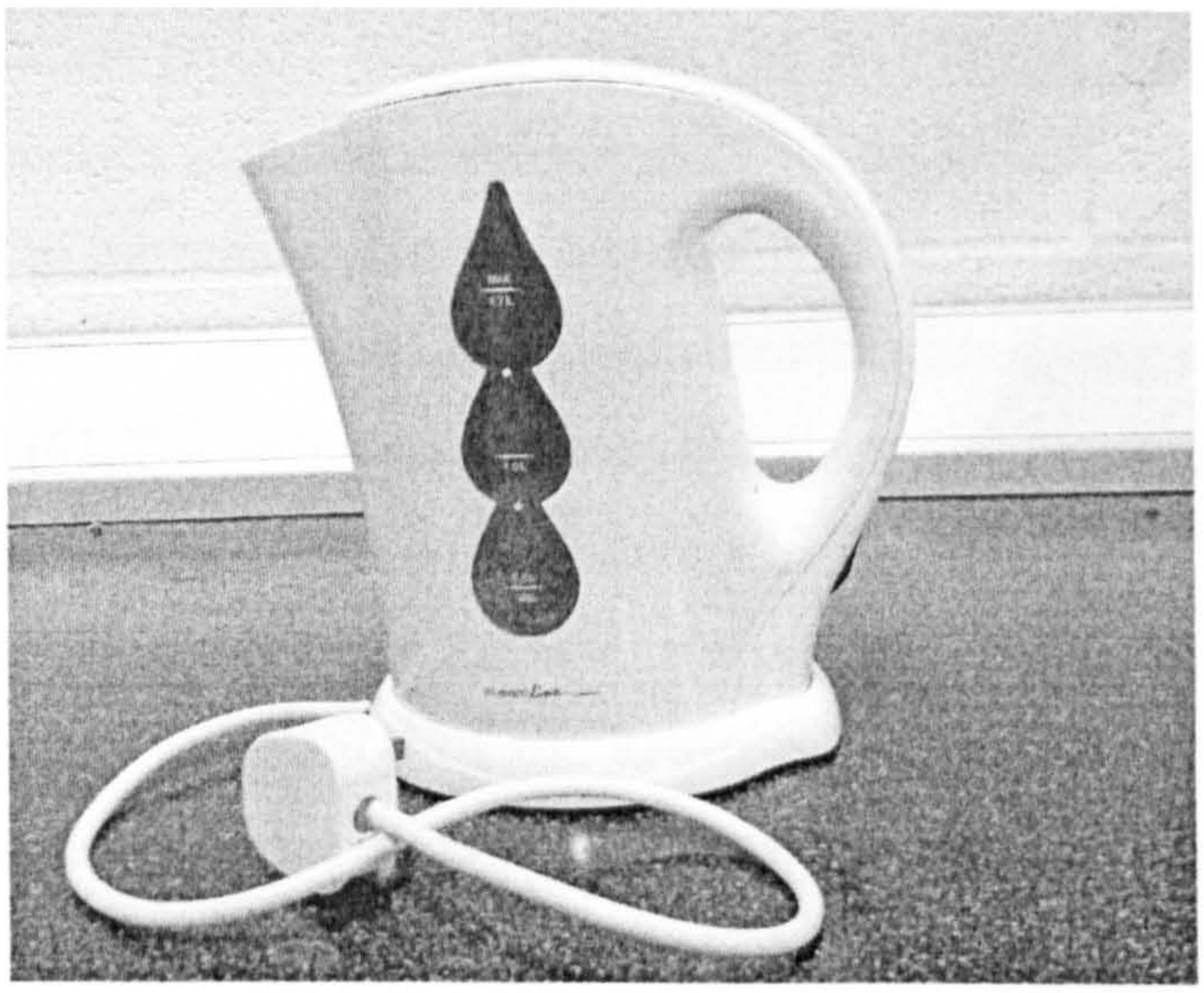


Figure 10.24: Case study 2: Electric kettle

10.5.1 Product Evaluation

The first stage in applying the RPP framework on the case study product is the product evaluation. The identification of the case study product and its category namely, the small household appliance, within the product evaluation process establishes the WEEE directives recovery and recycling requirements for the kettle as shown in Figure 10.25.

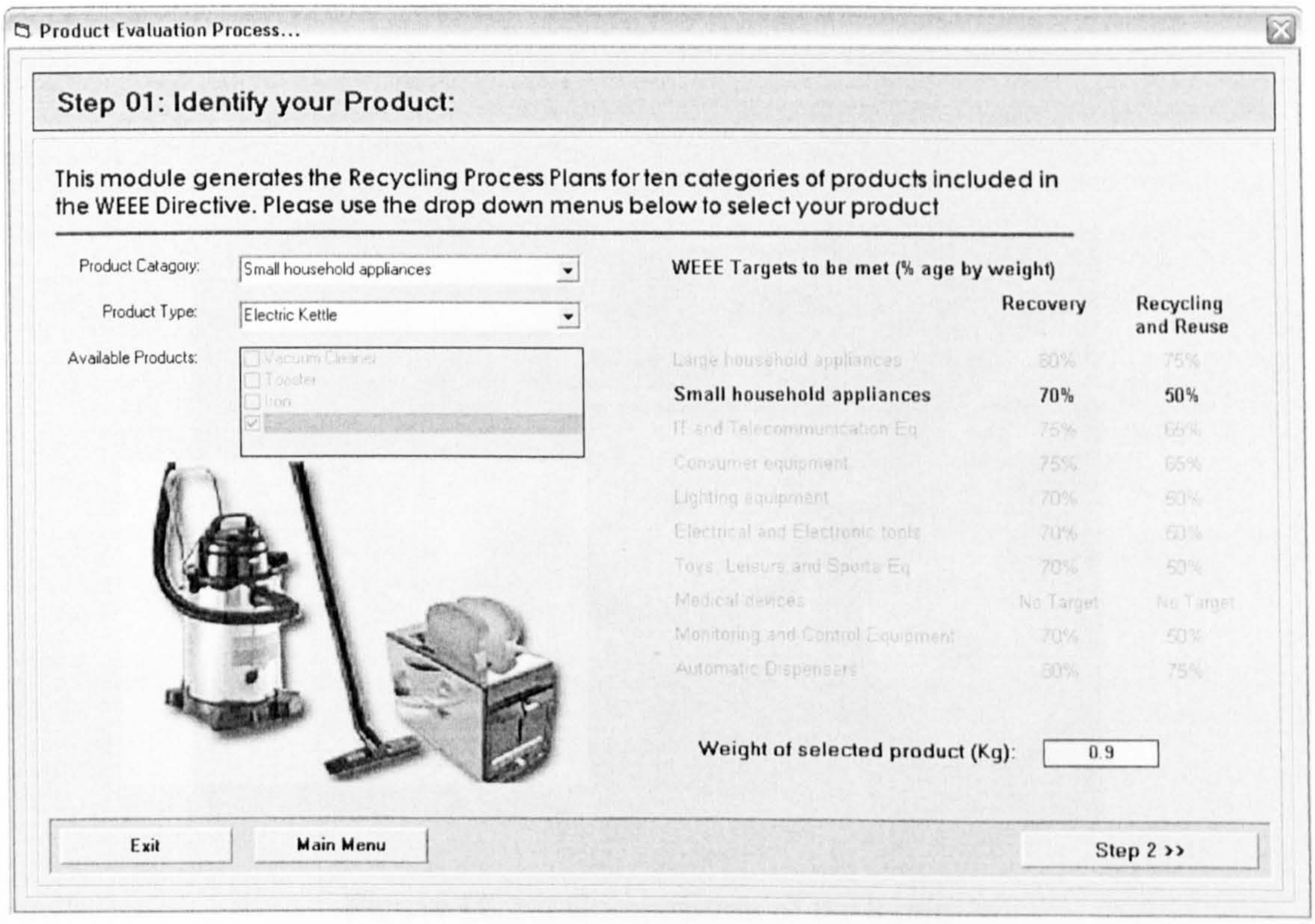


Figure 10.25: Identification of the case study product and its WEEE category

The product evaluation process also identifies the hazardous, valuable and penalty materials and components included in the kettle. With the exception of external electric cable which needs to be removed in the pre-treatment stage, there is not much to be removed from the kettle. The kettle is a simple product consisting of a polypropylene jug and power base (61.2%), nichrome (nickel-chromium alloy) heating element (14.4%) and an external electric cable (16.6%) (see Figure 10.26).

Based on the material composition of the kettle, appropriate recovery and recycling processes are assigned to the case study product. It is identified that the due to low value (in terms of both ecology and economy) contained in the kettle, it is best destined to shredding and post fragmentation separation of the materials.

10.5.2 Legislative Compliance Monitoring

The second stage of the RPP framework is used to identify the WEEE directive's requirements related to the recycling of the kettle which falls within the scope of the WEEE directive in the 'small household appliances' category. It is required to be separately collected from the household waste. As far as recovery and recycling targets for the kettle are concerned, WEEE directive requires 70% of its weight being recovered with at least 50% of its weight being recycled or reused.

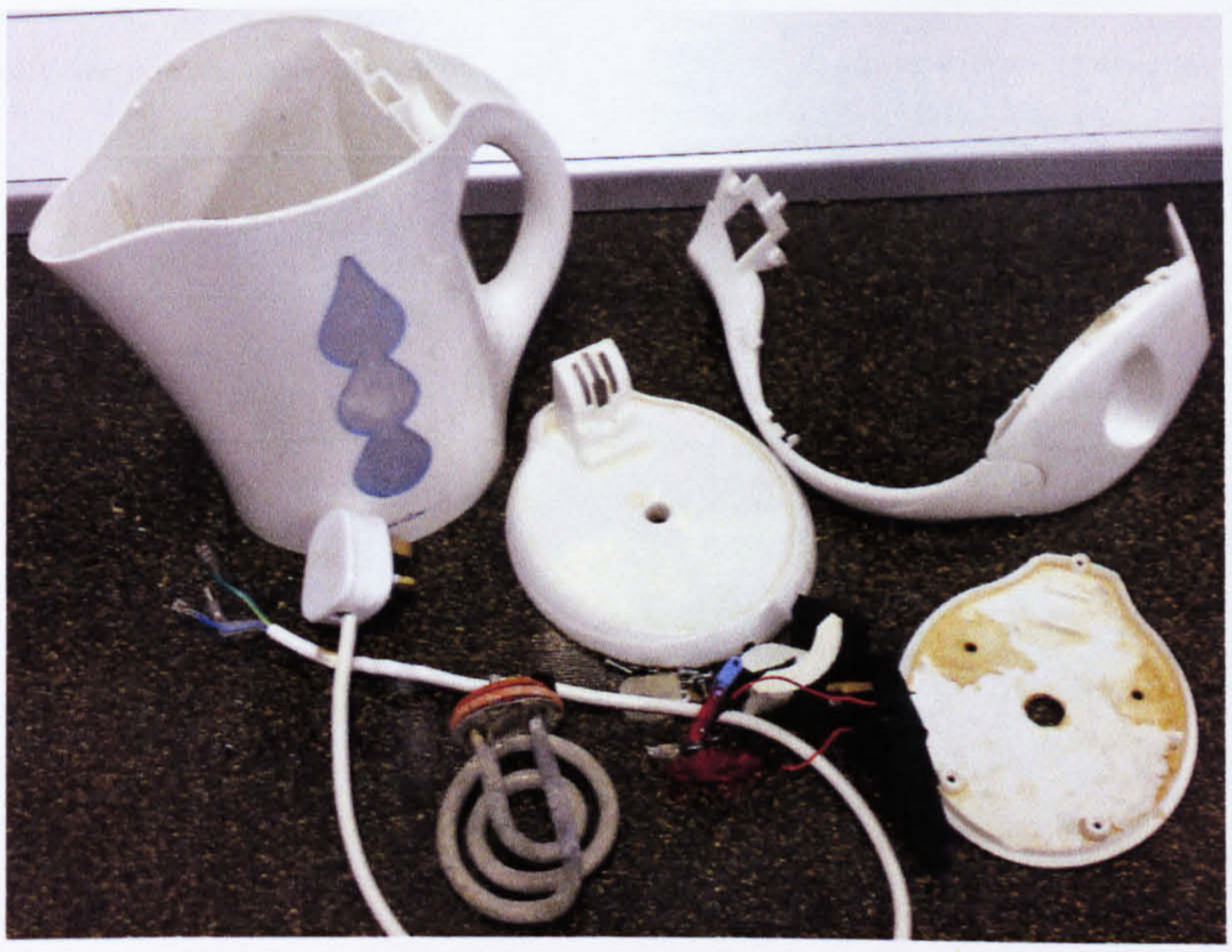


Figure 10.26: Composition of the kettle

10.5.3 Recycling Process Planning

In the third stage of the RPP framework a bespoke recycling process plan is generated for the kettle. Figure 10.27 depicts the bespoke recycling process plan for the kettle. It is clear that the major proportion of the materials included in the kettle is being processed through shredding.

With most of the materials in the kettle being recovered in the post fragmentation stage, the compliance monitor in the recycling process plan highlights that both the recovery and recycling targets will be easily met. In the next stage of the RPP framework, ecological and economical impacts associated with this bespoke recycling process plan are calculated and are compared with the overall performance of the kettle under other end-of-life options.

Recycling Process Plan...

Step 07: Recycling Process Plan for your Product

The Recycling process plan for: < Electric Kettle >

Recycle Product Name:	Electric Kettle
Recycle Product Category:	Small household appliances
Net Product Weight:	0.9
Total Hazardous Material Weight(kg):	0.15
Weight Sent to Shredder(kg):	0.75
Weight disposed as MWS(kg):	0.145

OP100 Depollution for legistlative compliance:

Process ID	Process Description	Weight Processed
Sub-Op109	Remove External electric cable for Material Recovery	0.15

OP200 Valuable parts recovery:

Process ID	Process Description	Weight Processed

OP300 Dismantling to remove Penalty substances:

Process ID	Process Description	Weight Processed

OP400 Shredding and Mechanical Separation:

Process ID	Process Description	Weight Processed
Sub-Op402	Use Air Separation to recover lighter fractions	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	0
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.117
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.042
Sub-Op409	Use Skin Floatation to recover FR plastics	0
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.364

OP500 Safe Disposal:

Process ID	Process Description	Weight Processed
Sub-Op501	Incinerate Air separation process fluff	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.008
Sub-Op503	Controlled incincration of other hazardous materials	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0
Sub-Op508	Dispose the waste as MWS	0.002
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.145

Weight of the Product Recycled	0.523
Weight of the Product Recovered	0.676

Compliance Monitor

Electric Kettle	Recovery (%)	Recycling (%)
Targets	70	50
Achieved	75.11	58.11
Compliance	Yes	Yes

Exit | Save Recycling Process Plan | Environmental Assessment of Recycling Process Plan >>

Figure 10.27: Bespoke recycling process plan for the kettle

10.5.4 Ecological and Economical Assessment

In the final stage of the RPP framework the ecological and economical impacts associated with the recycling of the kettle through recycling process plan option are calculated and compared with the impacts under current shredding practice and landfill options. Different tasks involved in the calculation of the ecological and economical impacts are described in detail in *Appendix 5* and only the results are presented here. The comparison of the ecological and economical performances of different end-of-life options for kettle within the assessment module of the CA***R***PP is illustrated in Figure 10.28. The comparison shows that the there is a small improvement in the performance of kettle under the recycling process plan option.

Finally, the ecological and economical performance ratios along with the combined performance ratio of different end-of-life options for the electric kettle are summarised in Table 10.3.

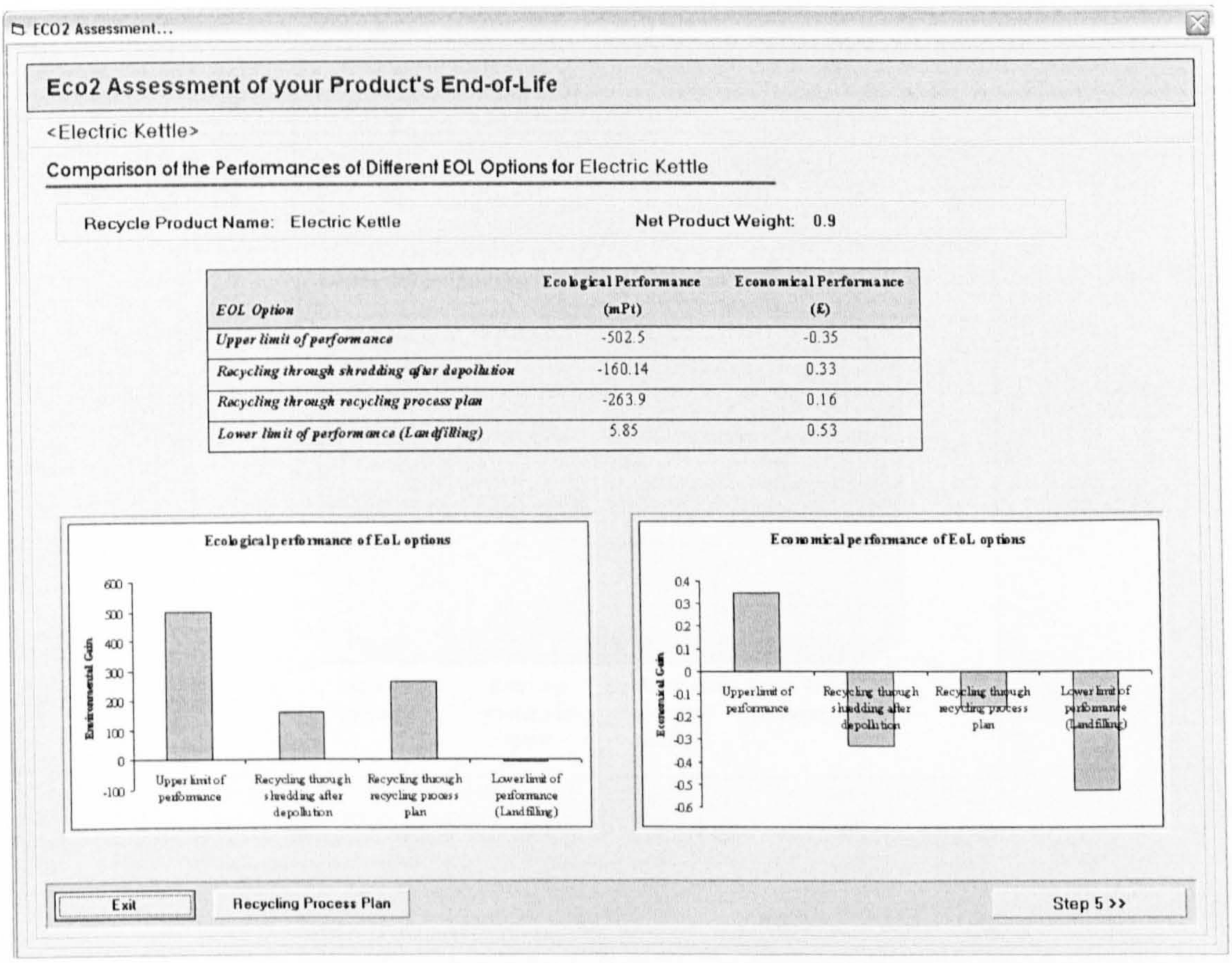


Figure10.28: Comparison of performances of different end-of-life options for the kettle

EoL Option	Ecological Performance Ratio (EPR_{ecol})	Economical Performance Ration (ERP_{econ})	Combined Eco^2 Performance Ratio (C*E*PR)
Upper limit of performance	1	1	**1**
Shredding after depollution option	0.327	0.228	**0.277**
Recycling process plan option	0.531	0.421	**0.476**
Lower limit of performance	0	0	**0**

Table 10.3: Performance ratios for different end-of-life options for the electric kettle

As previously stated, the higher value of C*E*PR (close to 1) represents a good overall performance of the assessed end-of-life option, it can be concluded that the overall performance of the recycling process plan option (C*E*PR = 0.476) is better than the shredding after depollution option (C*E*PR = 0.277) for the electric kettle as depicted in Figure 10.29.

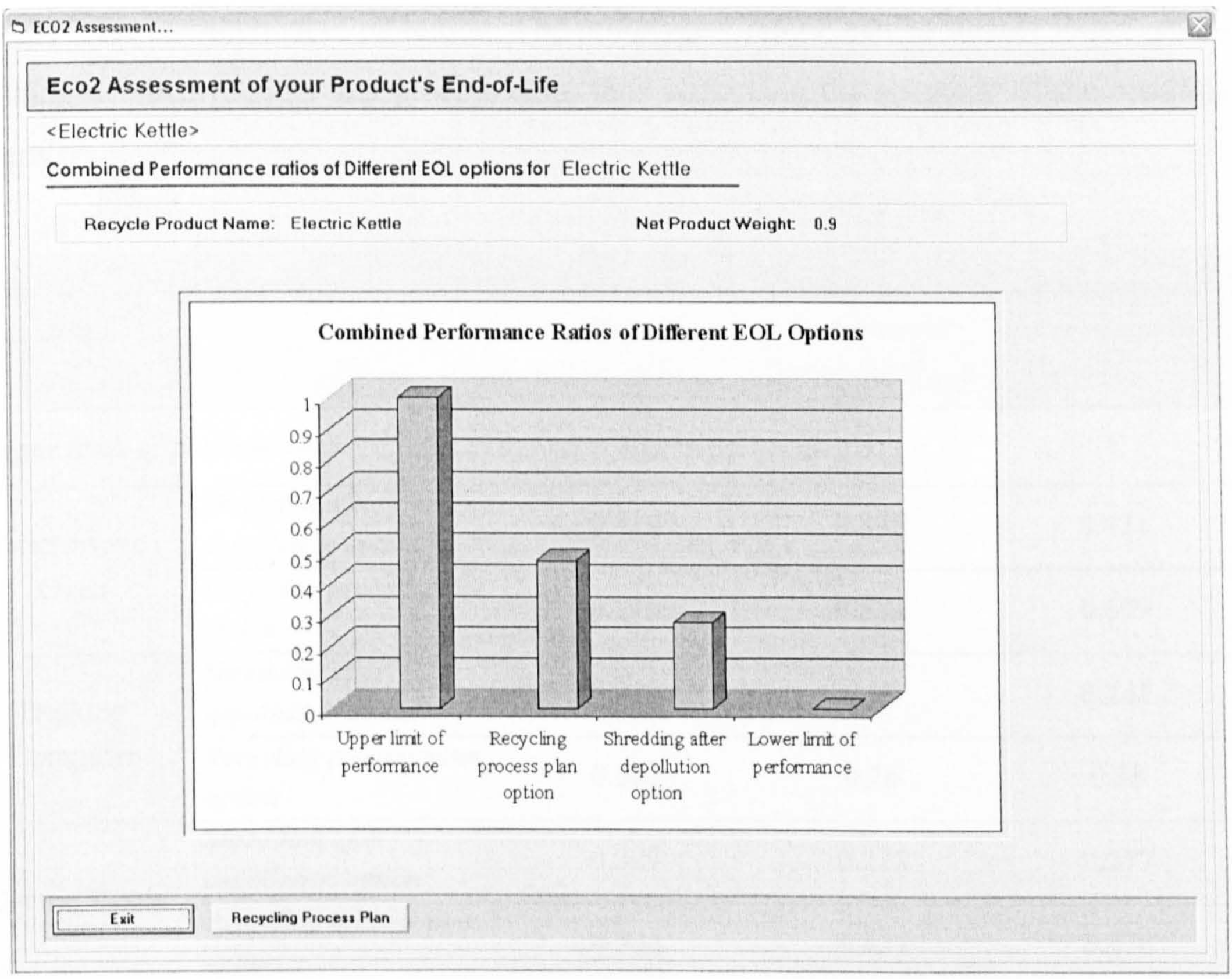


Figure 10.29: Overall ranking of different end-of-life options for electric kettle

10.6 Summary of Case Studies' Results

This chapter has successfully demonstrated the application of the RPP framework in terms of both the generation of the bespoke recycling process plan as well as the effective ecological and economical assessment method to identify the appropriate end-of-life option for the product under consideration. Three distinctively different types of products included in WEEE have shown the usefulness of the RPP framework in terms of identifying the appropriate legislative pre-treatment requirements as well as eco-efficient recovery and recycling processes based on product's material composition to be used for their recycling. In addition, the Eco^2 assessment of each case study has shown that a significant improvement can be achieved by recycling the product through the proposed bespoke recycling process plan as compared to the current state of the art and landfill options. Table 10.4 provides a comparison of the improvements in the end-of-life management of these case studies resulted by using bespoke recycling process plans. It is acknowledged that there is a lack of detailed industrial data incorporated within the CA***R***PP for commercial exploitation. The prototype CA***R***PP can be further improved by linking detailed product and process data, thus improving the accuracy of the resulting plans.

EoL Option		**Ecological Performance Ratio (EPR_{ecol})**	**Economical Performance Ration (ERP_{econ})**	**Combined Eco^2 Performance Ratio (C*E*PR)**
Upper limit of performance		1	1	**1**
Microwave Oven	*Shredding after depollution option*	0.514	0.348	**0.431**
	Recycling process plan option	**0.816**	**0.582**	**0.699**
Desktop Computer	*Shredding after depollution option*	0.312	0.17	**0.241**
	Recycling process plan option	**0.501**	**0.26**	**0.38**
Electric Kettle	*Shredding after depollution option*	0.327	0.228	**0.277**
	Recycling process plan option	**0.531**	**0.421**	**0.476**
Lower limit of performance		0	0	**0**

Table 10.4: Comparison of the case studies results

Chapter 11

Concluding Discussion

11.1 Introduction

The discussions included in this chapter bring together the major research issues examined by this research and reports on the research contributions provided by this thesis. The initial part of the chapter provides an overview of these research contributions, as identified by the author, and the later sections of the chapter bring together many of the points of discussion using the structure defined by the research scope in chapter 2.

11.2 Research Contributions

The author has identified the following points as the important contributions made by this research in the field of WEEE recovery and recycling.

i. Generation of a comprehensive end-of-life model to provide an overview of the current state-of-art WEEE recovery and recycling activities.

ii. Identification of a number of shortcomings in current WEEE recovery and recycling practices through a critical review of WEEE end-of-life model, and published work in this subject area.

iii. Development of a novel recycling process planning framework that addresses many of the current shortcomings by the generation of bespoke recycling process plans for WEEE, and enables the monitoring of legislative compliance.

iv. Development of a new and integrated methodology for parallel consideration of the ecological and economical performances of different WEEE recovery and recycling activities to support the selection of appropriate end-of-life options.

v. Design and implementation of a prototype CA*R*PP which provides a powerful tool for a systematic approach to develop bespoked and detailed recycling process plans for the products included in the WEEE, and to provide access to the latest recycling process information to operators in various facilities.

vi. A programme of case studies demonstrating the applicability of the new knowledge and potential benefits gained through a systematic framework for generation of recycling process plans through CA*R*PP.

11.3 Concluding Discussion

The following sub-sections draw together and discuss the results of the main research activities outlined as part of the thesis scope.

11.3.1 A Review of WEEE Recovery and Recycling

An extensive literature review carried out as part of this research has highlighted the growing interest among the research community, governments, various stakeholders in the electrical and electronic recovery chain, and consumers in the end-of-life management of WEEE. Consequently, there has been a significant research targeted at the traditional challenges related to product disassembly which has resulted in a number of dismantling methods and techniques that plays an important role in the overall economics of the end-of-life management. These disassembly methods and approaches were intended to increase the end-of-life dismantling through improved attachment methods and accessibility. However, one of the major research findings is that these measures have failed to sufficiently improve the economic feasibility of dismantling, and in majority of cases disassembly of electrical and electronic equipment still remains economically not viable. This is apparent by the review of current recovery and recycling practices which are mainly based on fragmentation and separation processes.

A substantial quantity of literature has investigated the role of product information in the end-of-life management of WEEE and identified a general lack of this information available to recyclers. Another alarming result of review activities in this research is that due to the implementation of the WEEE directive in the UK and in the other EU countries in which the recycling of WEEE is effectively subcontracted to independent

recoverers, the active involvement of the manufacturers in the product recovery and use of upstream design data to support downstream product recovery seems highly unlikely in the near future. This lack of synergy between manufacturers and recovery facilities has created a situation in which business survival and end-of-pipe economics, as opposed to long term environmental benefits which were intended by the WEEE directive, are guiding the end-of-life recovery and recycling of WEEE.

The literature survey has also highlighted that although there has been a lot of academic research which focuses on different areas of waste management and end-of-life product recovery, there has been a lack of practical implementation of decision support for systematic approach to product recovery procedures in the electrical and electronic recovery sector. This clearly highlighted the requirement for an integrated approach to improve the sustainability of the WEEE recovery sector through more effective and holistic planning of recovery and recycling processes which has been the main focus of this research.

11.3.2 Generation of an End-of-Life Model for WEEE

A review of current electrical and electronic waste arising has identified the wide range of products, the complexities in the material compositions among these products and most importantly the environmental damage they can cause due to the presence of a plethora of hazardous and toxic substances in them. The industrial review of the current activities in the WEEE recovery sector has also highlighted that the majority of current recovery and recycling applications of WEEE are often developed on ad hoc basis and mainly due to commercial reasons. Another observation from these initial review activities was that similar EoL product may be processed quite differently in different facilities. This is at times due to available resources and other times due to lack of knowledge/information on most up to date recycling processes. Furthermore, the recently introduced environmental legislation in electrical and electronic sector is impacting the recycling facilities mainly in two ways. Firstly, it puts constraints on how they operate in terms of treatment and disposal of equipment to make them more environmental-friendly. Secondly, it is forcing them to develop and establish profit making opportunity from recycling of WEEE for long term survival and sustainability. In wake of such legislative pressures, the author argues that the recycling facilities need

to improve the value recovery from WEEE recycling to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable environmental and economical cost. Hence, the integrated recycling process planning framework developed by this research has placed a particular emphasis on economical and ecological assessment of various end-of-life options. The end-of-life model described in this thesis encompasses various sources of waste creation, disposal routes and recycling options, and provides a holistic view of available EoL options for WEEE.

11.3.3 Development of a Recycling Process Planning Framework

There are a large number of recovery facilities that are being set up in various EU countries to process a huge volume of a wide range of electrical and electronic products in response to the requirement for massive increase in recovery capacity to meet the target set by the WEEE directive. It is apparent that the immediate challenge for these recycling facilities are to minimise the overall costs for end-of-life treatment of discarded products (i.e. economically justifiable) and at the same time to maximise the environmental benefits of such recovery and recycling activities (i.e. ecologically friendly). This highlighted the need to explore multi-objective optimisation for generation of process plans for WEEE recycling activities which includes legislative compliance monitoring, and ecological and economical assessment. The recycling process planning framework described in this thesis further extends the previous research in end-of-life management of WEEE by considering best possible sets of trade-offs between environmental and economical variables, and more importantly by including simultaneous consideration of the macro and micro level end-of-life planning to determine an appropriate sequence of recycling processes for individual products in WEEE. It is argued that the adoption of such recycling process planning framework for the generation of bespoke recycling process plans for various products in WEEE will significantly improve their end-of-life management. In addition, the author is of the opinion that though the recycling process planning framework has been developed specifically for the electrical and electronic sector, it offers great potential for re-application in other industrial sectors (e.g. automotive etc.).

11.3.4 An Ecological and Economical Assessment Methodology for WEEE

A common problem reported in the research related to the end-of-life management of WEEE is to determine to what extent return products must be disassembled and which product recovery option should be applied while minimising the environmental and economical impacts of product recycling. The wide range of products in WEEE and the complexity of materials in each product do not allow one end-of-life option to be used for different products. As each end-of-life option involves varying amount of economical and environmental costs, and therefore selection of appropriate options for treating electrical and electronic equipment is of paramount importance for the effective end-of-life management of WEEE. This highlights the need for a systematic ecological and economical assessment methodology to aid decision making involved in the selection of the best possible end-of-life strategies for individual products in WEEE. The Eco^2 assessment methodology presented in this research is unique in that it provides a simple but effective process to calculate the ecological and economical impacts of various end-of-life options for WEEE in the form of ecological and economical performance scores which are easier to interpret than the conventional life cycle assessment results. These ecological and economical performances scores are later combined into a single performance ratio, which can be used as a decision support criteria to identify the most appropriate end-of-life option for the product under consideration. The author is of the opinion that such concurrent analysis of the environmental impacts and cost of recovery and recycling activities can efficiently simplify and significantly improve the end-of-life management of WEEE.

11.3.5 The Realisation of a Computer Aided Recycling Process Planner to Support Recycling Process Planning

During this research, it became apparent that a number of competing criteria had to be considered and analysed to identify the best solution for WEEE recycling. The determination of the most appropriate end-of-life option to recycle the product under consideration, as described in chapter 7 and 8, is a complex task consisting of data processing related to a wide range of end-of-life issues such as varying material composition, weight and product structure, product age and condition, various recycling processes and technologies, and their environmental and economical impacts. This

highlighted a need for a software decision support tool. The CA*R*PP has provided a fast and effective means of generating the bespoke recycling process plans as well as Eco^2 assessment results for a number of case studies that would otherwise require intensive data collection and laborious analysis if done manually.

Although, the CA*R*PP has been designed and implemented to support the end-of-life management of WEEE, the author argues that this software tool can also provide invaluable support for design and material selection activities in electrical and electronic sector in order to facilitate recycling of future WEEE. One further advantage provided through utilisation of CA*R*PP is the provision of most up-to-date recycling processes (stored in databases) to various recovery facilities, thus harmonising the treatment of various products in WEEE in various EU countries.

11.3.6 Demonstration of Research Applicability through Case Studies

For the purpose of validation and demonstration of the research concepts, three case studies on the implementation of the RPP framework have been defined and undertaken. A clear objective of these case studies was to follow a stepwise implementation of the RPP framework proposed by this thesis, and to show its feasibility and applicability in selecting the most eco-efficient recycling route for individual product among the wide range of products included in WEEE. Three distinctly different products from different categories of WEEE, namely microwave oven (metal dominated), desktop computer (suitable for reuse), and electrical kettle (non-metallic, low value) have been selected to provide a broader perspective for the evaluation of the research concepts. These case studies have demonstrated the usefulness of the recycling process planning framework in terms of identifying the legislative requirements and most relevant recovery and recycling processes for the product under consideration. Furthermore, the Eco^2 assessment of various end-of-life options for each case study has clearly underlined the substantial improvement that could be achieved in the environmental and economical performance of WEEE recycling activities through adoption of a systematical approach for generation of a recycling process plan based on the most up-to-date information and knowledge on recycling processes, contained within the CA*R*PP.

11.3.7 Contribution to Knowledge and Industrial Practices

A novel recycling process planning framework taking advantage of the benefits provided by a systematic approach to process planning experienced in manufacturing applications has been generated by this research. The application of this new recycling process planning knowledge in the end-of-life management has shown an improvement in the efficiencies and ecological and economical performances of WEEE recycling activities. A new and integrated ecological and economical assessment methodology has also been developed by this research. The contribution to the existing field of knowledge by this Eco^2 assessment methodology is the provision of a simple but effective process to calculate the ecological and economical performances of different EoL options for WEEE recycling as well as the normalizing scales and combined analysis of ecological and economical performances. The Eco^2 assessment and a legislative compliance monitor are integrated with the RPP framework to provide a holistic decision support to determine the appropriate EoL options for WEEE recycling.

To fulfill the need to improve the end-of-life management of WEEE and to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable cost, any used product that is received for the first time by a recovery facility should be examined in an assessment workshop, before determining the recovery processes required to be used for the product. It is envisaged that the CA*R*PP developed by this research can be used within such assessment workshops to speed up, introduce consistency and improve the development of bespoke recycling process plans which are based on most updated information and knowledge related to existing recycling processes. These recycling process plans can then be stored in an operational database and applied to similar product families in the future. It is envisaged that CA*R*PP would allow manufacturers as well as recyclers to determine the end-of-life costs associated with particular products upfront leading to better cost negotiations, which would encourage manufacturers designing their products with considerations for end-of-life.

11.3.8 The Vision for the Future of WEEE Recovery and Recycling

A common trend in the production of electrical and electronic equipment is the reduction of precious metal which has been the focus of economically driven recycling of WEEE.

This reduction of the hidden value and legislative pressure for adopting environmentally friendly recycling processes will significantly impact the economics of WEEE recycling in future. This clearly highlight a need on one hand to reduce the cost of recycling most probably through increased automation and on the other hand the need for better value recovery from WEEE through increase rate and quality of materials recovered.

It is argued that the way in which WEEE directive has transposed the WEEE recovery chain in the UK, whereby manufacturers are being charged a flat rate for meeting their recovery and recycling obligations in a collective system by the producer compliance schemes has eliminated any motivation for green design or green products. However, the current solution of meeting the recovery and recycling obligations at a marginal cost is very much dependant on the current high scrap metal prices and lacks long term sustainability. Any change in the scrap metal price or increase in recovery and recycling targets can have severe impact on the whole economics of WEEE recovery and recycling. In addition, the current targets included in WEEE Directive needs to be re-evaluated based on the actual environmental gain and economical ramifications to provide more meaningful guidelines for the emphasis in WEEE recycling.

Finally, the greatest environmental challenge which lies ahead is the need to adopt sustainable pattern of production and consumption. Recycling, despite being better than landfilling, is still an industrial activity with its own environmental and economical impacts. A positive change in the business models is through adoption of Product Service System in which the revenue for the producer is generated through the provision of the service required by the customer. In this approach the emphasis is on developing modular and durable products as the manufacturer is responsible for the product during its life cycle, and has the potential for significant reduction in the environmental and economical impacts in the product end-of-life management.

Chapter 12

Conclusions and Further Work

12.1 Introduction

This chapter presents the conclusions drawn from this research and suggests several areas where further work is needed, based on the research conveyed in this thesis.

12.2 Conclusions

The conclusions drawn from this research are as follows:-

i) The rapid increase in the amount of waste from electrical and electronic equipment which contains substantial quantities of hazardous content clearly indicates the need for further investment and improved procedures for recovery and recycling of WEEE.

ii) The review of current WEEE recycling practices in this research has indicated that these applications have been developed on ad hoc basis and mainly due to the hidden economic value within used products. On the other hand, one of the recent trends in electrical and electronic equipment manufacturing has been the gradual reduction of the amount of precious metals and other valuable materials contained in these products. This reduction of hidden value together with additional cost of meeting legislative requirements further highlights the need for provision of effective decision support tools to the recyclers to improve the environmental and economical performance of their recovery activities to ensure long-term sustainability.

iii) The WEEE directive was aimed at extending the manufacturers responsibility to encompass end-of-life considerations in their product design and to make them directly involved in the recovery of their products. However, the implementation of this directive in most EU countries including in the UK, in the form of

collective producer compliance schemes that charge a flat rate per tonne for compliance, has resulted in the manufacturers having no direct economic interest or influence on WEEE recovery, thus eliminating any motivations for the improved design and material use. Furthermore, this research has identified that the lack of product information available to recyclers, results in inconsistencies and inefficiencies in recycling of such waste. These are clear indications of the need for new drivers (economical or legislative) to encourage the active involvement of the manufacturers in the product recovery and the use of upstream design data to support downstream product recovery.

iv) The wide range of products and materials contained within WEEE together with the wide range of legislative requirements, and environmental and economical impacts of different recovery and recycling processes has resulted in a complex end-of-life management of electrical and electronic waste. The novel and integrated approach generated by this research to produce bespoke recycling process plans for various products in WEEE has been shown to improve their end-of-life management.

v) The parallel consideration of the environmental and economical impacts of different recovery and recycling processes through Eco^2 methodology provides a simple but effective process to calculate the ecological and economical impacts of various end-of-life options for WEEE. The impacts of each EoL option are calculated in the form of ecological and economical performance scores and are combined in a single performance ratio which is easier to interpret and use than the conventional life cycle assessment results. The author believes that the Eco^2 assessment can significantly improve the end-of-life management of WEEE by supporting the decisions involved in the selection of most appropriate end-of-life options for individual products.

vi) The computer aided recycling process planner has been shown to be a powerful tool for a fast and effective method of accomplishing the complex task of generating the bespoke recycling process plans and to provide access to the up-to-the-date knowledge and information on materials and recycling processes to various recycling facilities.

vii) The case studies described in this thesis have effectively demonstrated the applicability of the research concepts. Furthermore, the results from these case studies have also shown the impact that the proposed recycling process planning framework could have in identifying many improvements which could be made in current recovery and recycling practices.

viii) The WEEE directive ultimately makes the manufacturers of electrical and electronic equipment responsible for take-back and recycling of WEEE. The current producer compliance schemes are reliant on the high value of scrap metal and any change in this market may significantly impact their ability to deliver the legislative compliance requirements. Therefore, the author believes that manufacturers must take a more pro-active and direct involvement in WEEE recovery through further investment in environmentally friendly approach to design and product recycling that ensures the long-term sustainability and survival of the WEEE recovery sector.

12.3 Further Work

The author acknowledges the following areas for further work as a result of this research:-

12.3.1 Detailed Material Composition of WEEE

The material composition data used within the CA*R*PP was developed from a number of academic studies on generic composition of different categories of WEEE. However, this data is limited in terms of exact product material composition as well as part/component material composition. Therefore, future research is needed to identify the detailed material composition data of different electrical and electronic products as well as their parts and components to augment the existing data included in the CA*R*PP.

12.3.2 Life Cycle Assessment Enhancement

In this thesis a simple but very effective Eco^2 methodology is developed for a streamline environmental impact assessment to calculate the ecological and economical impacts

involved in the end-of-life management of different products included in WEEE. During the course of this research, it has been observed that the end-of-life phase is often neglected or not properly addressed in life cycle assessment software and related approaches. The environmental impacts of various EoL processes (e.g. landfill, incineration, recycling etc.) are based on rather idealistic and optimistic situations giving rise to the identification of the negligible impact during end-of-life which is often not the case in actual practice. Therefore, further work is needed to properly encompass the end-of-life stage in LCA software and related approaches by identifying the actual environmental impacts of different materials as well as recovery and recycling processes in real life situations.

12.3.3 Use of Embedded Information Devices to Provide Product Evaluation

This research has developed a multi-task product evaluation process to collect the information required for recycling process planning and subsequent decision involved in the end-of-life management of WEEE. However, it is envisaged that the emerging technologies like Radio Frequency Identification, and other embedded information devices such as iButtons etc. can be used to store and directly transfer the product information to CA*R*PP thus eliminating the need for product evaluation. This would allow the automatic generation of the recycling process plans through the CA*R*PP.

12.3.4 Application of Recycling Process Planning in Other Industrial Sectors

This research has proposed the recycling process planning approach to support the planning of recovery and recycling activities in electrical and electronic sector. The range of products in WEEE and varying material compositions in different products warrants the use of recycling process planning. The author is of the opinion that further work is required to investigate the suitability of this approach for other industrial sectors. However, it is recognised that application of RPP framework and associated CA*R*PP in other sectors requires modifications and maybe some customisation.

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Appendix 1

An End-of-life Model for Waste Electrical and Electronic Equipment Recycling

Introduction

This paper was presented at the 5th International Conference on Design and Manufacture for Sustainable Development in Loughborough in 2007.

An End-of-life Model for Waste Electrical and Electronic Equipment Recycling

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ABSTRACT

The ever-increasing amount of waste electrical and electronic equipment (WEEE) has become a common problem facing the world today due to the significant environmental and health impacts associated with its current end-of-life management. To tackle this problem, the European WEEE directive requires companies who manufacture or import electrical and electronic equipment to take financial and legal responsibility for its environmental-friendly end-of-life management. The current recycling applications of electrical and electronic waste are often developed on an ad hoc basis, mainly due to the hidden economic value within used products. This highlights the need to improve the value recovery from WEEE recycling activities to ensure that a larger proportion of components and materials are being recovered at a reasonable cost and yet at the same time, legislative requirements are being met. Hence, this paper presents an end-of-life model to improve the recyclability and value recovery from electrical and electronic waste recycling. The areas of concern in WEEE recycling identified through the end-of-life model are addressed by a computer aided recycling process planner.

1 INTRODUCTION

The production of Electrical and Electronic Equipment (EEE) is one of the fastest growing sectors of the manufacturing industry today. New applications of EEE are increasing as these products are becoming more and more a part of people's daily life. At the same time, both technological innovation and shorter product life cycles continue to accelerate the replacement of EEE leading to significant increase of Waste Electrical and Electronic Equipment (WEEE) (European Commission 2000). It has been predicted that 7.3 million tonnes of WEEE was generated in west Europe in 2002, with an estimated annual growth rates of 3 – 5% (Hesselbach *et al.* 2001). Although a part of this waste (mainly metal dominated white goods) has been recycled, a large proportion of WEEE that contains potentially recyclable materials ends up in landfills. WEEE is non-homogenous and complex in terms of materials and components and includes highly toxic materials such as chlorinated and brominated flame retardants, toxic metals, acids, mercury, lead and cadmium. With these hazardous elements WEEE can cause serious environmental and health problems during disposal if not pre-treated (European Commission 2000, Macauley *et al.* 2003). The over-exploitation of scarce materials in the manufacture of EEE and its dumping into scarce landfill sites, along with the environmental problems caused by EEE waste has resulted in the introduction of an European directive for such waste, namely the Waste Electrical and Electronic Equipment Directive.

The scope of this Producer Responsibility directive targets producers, distributors, consumers and all parties involved in the treatment of WEEE and it aims to reduce the amount of WEEE going to landfills, increase reuse, recycling and other forms of recovery and reduce the environmental impacts associated with the end-of-life (EOL) phase of EEE (European

Commission 2003). In its simplest sense the directive requires EEE manufacturers to finance collection, treatment and recycling/recovery of separately collected WEEE to the specific treatment standards and meet recovery/recycling targets of 70-80% by weight depending on the type of WEEE.

Figure 1, Waste from Electrical and Electronic Equipment

In the UK, many EEE manufacturers have opted to conform to the WEEE directive by moving away from actively fulfilling the requirements themselves, in favour of utilising producer compliance schemes. Currently, the recovery treatment of this waste is mainly based on the capabilities and available resources within EEE recovery facilities, without detailed consideration of the environmental benefits of such recycling activities. Furthermore, these recycling activities are solely focused on the reclamation of the most valuable components and materials, with a substantial amount of waste still being sent to landfill in form of shredder residue. This highlights the need to improve the value recovery from WEEE recycling to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable cost and yet at the same time, legislative requirements are being met.

This paper presents an end-of-life model to improve the recyclability and value recovery from electrical and electronic waste recycling. The initial sections of the paper present the relevant literature and the current legislative situation in the UK as well as an end-of-life model to provide an overview of current EEE recovery and recycling practices. The areas of concern in current EEE recycling identified through the end-of-life model, are further discussed to develop the requirements for a systematic eco-efficient approach to recycling process planning described towards the end of the paper.

2 BRIEF REVIEW OF THE MOST RELEVANT RESEARCH

The two important aspects considered in EOL research are recycling cost and environmental impact. These aspects should form the basis for any recycling strategy selection. Existing

research however usually focus on the economic aspects of EOL recycling. Most of the studies for recycling cost estimation have adopted a bottom-up approach where the estimation is conducted based on operation breakdown and summation of detailed cost items. For material recovery, several studies estimate recycling cost including disassembly cost, shredding and separation cost, disposition cost and revenue from reclaimed materials. Reimer et al. (2000) have proposed a recycling model to minimize the cost of different EOL activities like collection, disassembly, and material separation sequences by establishing separate models for each activity and using genetic algorithms. Other examples include Tsao (2001) and Stutz *et al.* (2002). Much attention is paid to disassembly as it plays an important role in recycling economics. Tang *et al.* (2004) and Gerner *et al.* (2005) systematically investigated the disassembly sequence and related operations so that disassembly cost can be optimised.

On the other hand, there is also an ongoing research to evaluate the environmental performance of different recycling scenarios. There is the life cycle assessment which is commonly used to determine the environmental impacts of a product throughout its life time. Some studies have incorporated both cost estimation and environmental impact estimation. For example, Lee *et al.* (2001) tried to find alternative that can both maximizes profit and minimizes environmental impact and use a coffee maker as an example. Zhang *et al.* (2000) adopted Analytical Hierarchic Process (AHP) to find the best recycling strategy. The AHP based evaluation considered environmental impact, cost and reclaimed materials as the major criteria for strategy determination. Huisman *et al.* (2003) described 'the quotes for the environmentally weighted recyclability' or QWERTY approach which focuses on the determination of environmentally weighted recycling scores. The concept describes the environmental performance of recycling of waste products. It is evident from the survey of relevant research that a holistic approach considering both environmental and economical impacts for different recycling options can provide invaluable decision support to achieve sustainable solutions in WEEE recycling.

3 WEEE DIRECTIVE AND ITS IMPLICATIONS WITHIN THE UK

The UK Government's WEEE Regulations introduce a new system for the management of WEEE in the UK from 1 July 2007, in accordance with the requirements of the EU WEEE Directive (Department of Trade and Industry 2007). The WEEE Directive requires the UK to:

- Maximise the separate collection of WEEE from other forms of waste;
- Ensure this WEEE is treated appropriately to protect the environment;
- Re-use, recycle and recover WEEE to target levels, and beyond the metallic content, for environmental protection and to contribute to greater levels of sustainable development;
- Dispose of any residual WEEE in an environmentally sound manner.

The UK Government has expressed an interest for the WEEE system to work in practice through the interactions among Producers, Distributors, Producer Compliance Schemes (PCS), Designated Collection Facilities (DCF) and Approved Authorised Treatment Facilities (AATF) (Department of Trade and Industry 2007). Producers of EEE can join the PCS to discharge their obligations under WEEE regulations. Distributors can chose between in-store take back or Distributor Tack-back Scheme (DTS). DTS will essentially give the customers free access to locally operated DCF. DCFs will be either existing local authority civic amenity sites, independent sites operated by third parties or retail platforms established as a result of distributors offering a collection on delivery services to their customers. These collection facilities will allow WEEE to be separately collected under five categories (large household appliances except cooling appliances, cooling appliances, display equipment

containing CRT, gas discharge lamps and all other WEEE). PCSs are required to provide evidence of discharging their members' obligations to finance the collection of WEEE from DCF, treatment, and reprocessing and recovery of WEEE at an AATF in line with their obligations. Producer obligations are based on their UK market share and the level of WEEE arising at DCF. PCS will need to establish commercial relationships with AATFs to ensure all WEEE is treated and reprocessed in accordance with the WEEE Regulations and appropriate WEEE Treatment Regulations. Only evidence issued by an AATF will be accepted by the environment authorities as proof that obligations have been correctly discharged under the Regulations. Figure 2 shows the main actors in the proposed WEEE recovery chain in the UK.

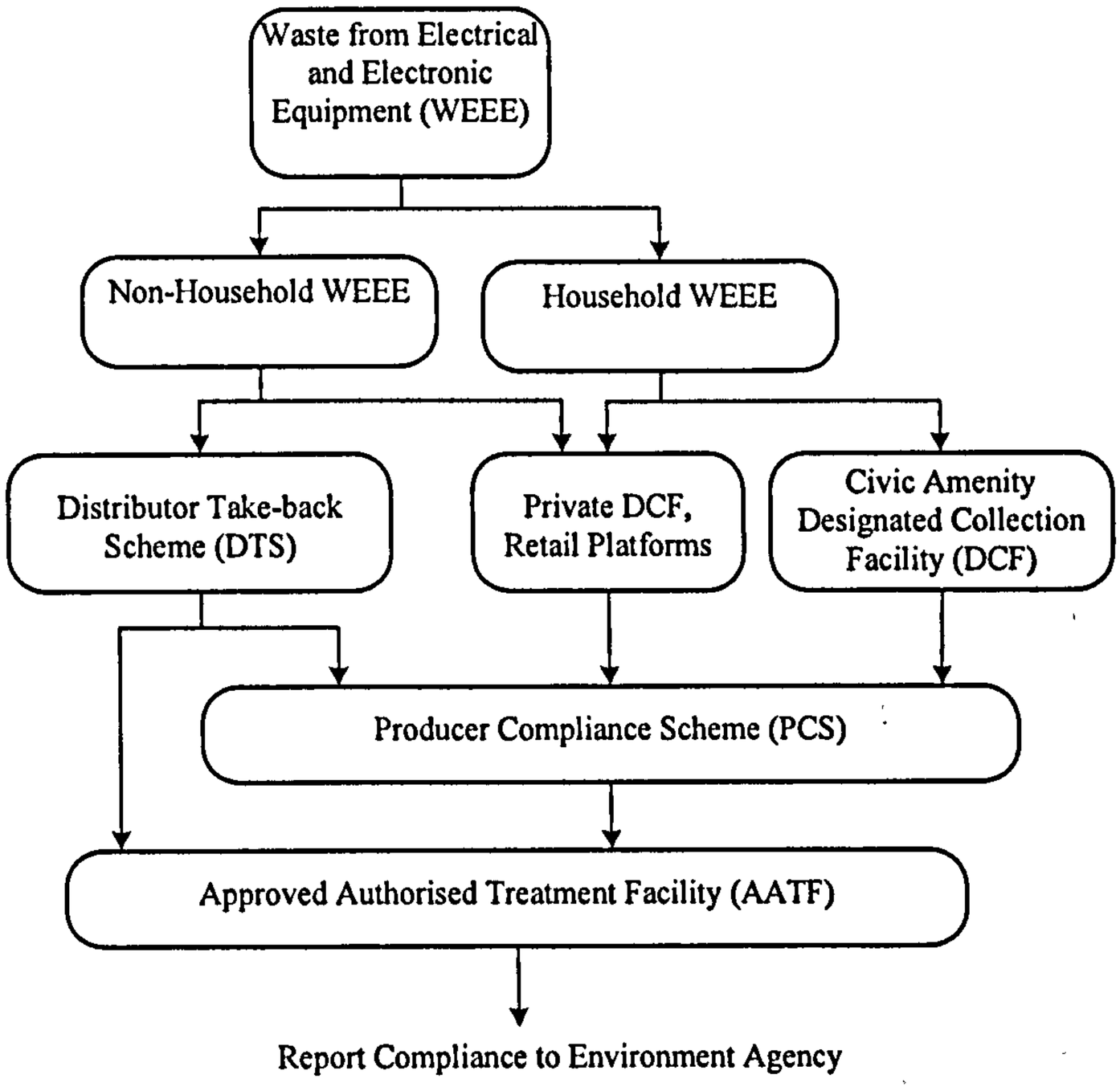

Figure 2, Proposed WEEE Recovery Chain in the UK

Historically in the UK, WEEE has either not been separately collected from other forms of waste, or where it has been separately collected it has not been treated prior to reprocessing (with the exception recently of refrigeration equipment, cathode ray tubes, and gas discharge lamps). Where WEEE has been recycled in the UK prior to the WEEE regulations it has primarily been undertaken for purely commercial reasons to obtain the value from secondary metals resulting in substantial quantities of waste being sent to landfill sites without any treatment.

4 AN END-OF-LIFE MODEL FOR WEEE RECYCLING

The end-of-life activities for EEE generally include separate collection, transportation, storage, pre-treatment (removal of hazardous substances), treatment (refurbishing, disassembly, shredding) and recovery (material recovery) (Cui and Forssberg 2003). Households provide the majority of end-of-life appliances. A smaller number come from appliance retailers and servicers, who typically take back old major appliances when installing new ones. A third source of used appliances is so-called "demand side management" or "early turn-in" programs where electric utilities give their customers

incentives to turn in older, less efficient appliances (primarily refrigerators and freezers). EEE is typically divided into large household appliances, IT equipment and small electrical appliances. Presently they are treated in the following way:

- **Large appliances** are mainly collected together with scrap metals at the municipal collection centres. After the dismantling and removal of Polychlorinated Biphenyl (PCB) capacitors and mercury containing components (switches), this fraction is added to scrap metals and mechanically separated in coarse shredding facilities.

- **IT Equipment & appliances with Cathode Ray Tube (CRT)** are gathered separately and dismantled. Casings (plastic and partly wood) are separated and presently still landfilled. Hazardous components like large capacitors and buffer batteries and accumulators as well as liquid crystal displays are removed and specially treated as hazardous waste.

- **Small electrical appliances** are at first submitted to the removal of hazardous components (for instance switches and relays containing mercury, PCB capacitors, batteries, etc) and these parts are forwarded to specific treatment options according to the special type of pollutant. The appliances of which the hazardous fractions are removed are mechanically processed. Through this treatment procedure, mainly metal-containing fractions are recovered. The remaining fraction containing mainly plastic are thermally treated or landfilled.

An end-of-life model for WEEE recycling summarising the various sources of waste creation, disposal routes and recycling options available to manufacturers is presented in Figure 3.

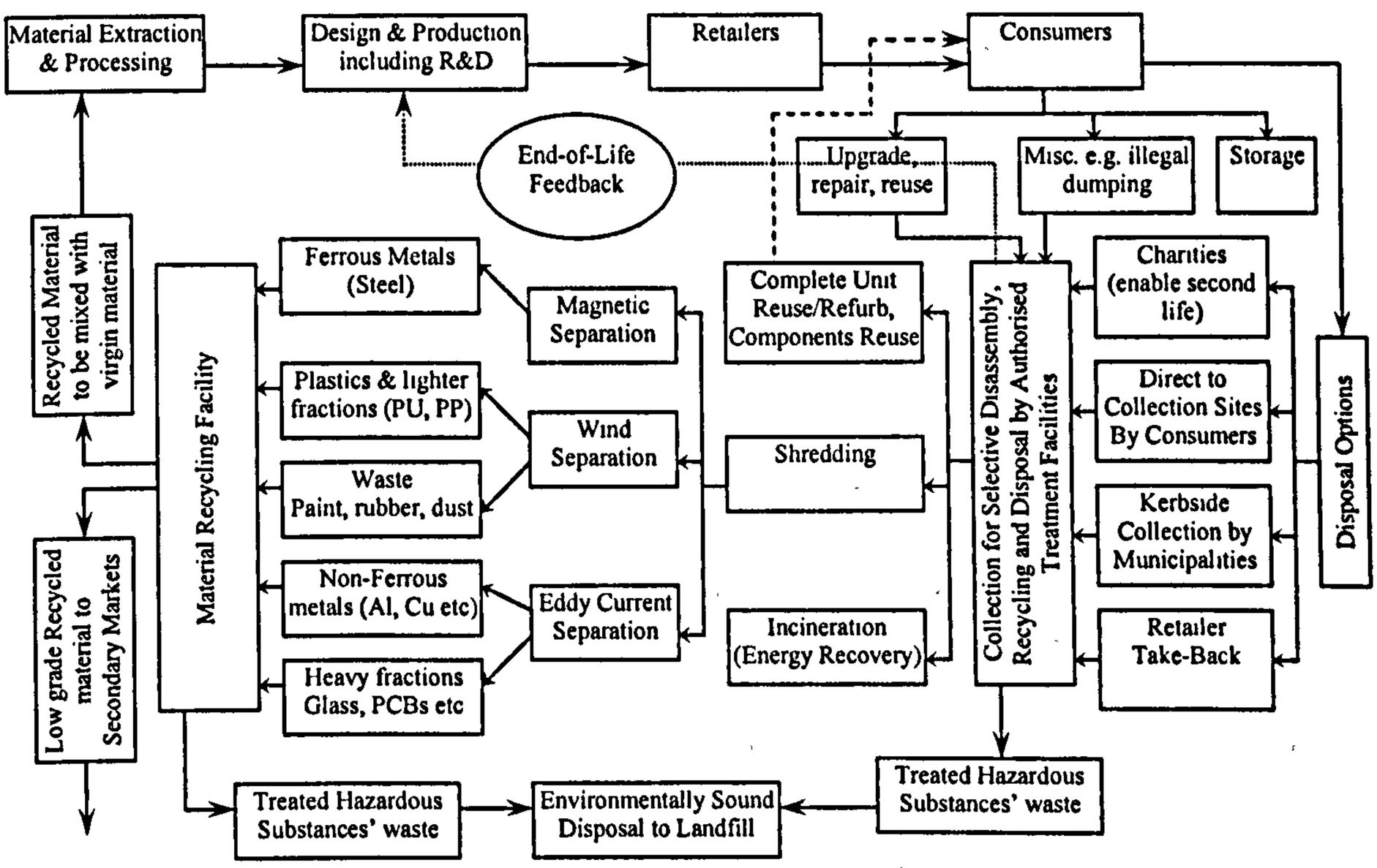

Figure 3, An EOL Model for WEEE Recycling

5 CURRENT OBSTACLES IN WEEE RECOVERY IN THE UK

The review of EOL activities within different recovery and recycling facilities has highlighted that the current issues of WEEE recovery relate to recovery practices driven by economical

reasons, lack of product data to facilitate recycling, lack of manual disassembly to recover high value components, contaminations in post-shredder material streams and most importantly inefficiencies in ad hoc applications of WEEE recovery due to lack of formal procedures to determine the best course of action for individual products. These issues and problems associated with them are described below:

- ***Recovery practices driven by economical reasons:*** Historically in the UK, metal dominated products (white goods) have been targeted for recycling with other metallic streams (like automobiles) to recover the ferrous metals. Where WEEE has been recycled in the UK prior to the WEEE Regulations this has primarily been undertaken for purely commercial reasons to obtain the value from secondary metals without any consideration to the environmental performance of the recycling strategy, resulting in substantial quantities of waste being sent to landfill sites without any treatment.

- ***Lack of product data to facilitate recycling:*** Product structure and material composition is a prerequisite for making an informed decision about selecting a recycling strategy for a particular product. However, currently in most cases access to this product data is not available to recyclers resulting in inconsistencies and inefficiencies in recovery treatment of WEEE.

- ***Lack of manual disassembly to recover reusable parts and materials:*** The manual disassembly of parts and materials has never been attempted by the majority of recovery facilities. One of the reasons being lack of awareness among recyclers about the reuse and value potential in a particular product. WEEE being a mixture of various materials can be regarded as a resource of metals, such as copper, aluminium, gold, and plastics and contain reusable high value components which can be reused through repair and refurbishment.

- ***Contaminations in post-shredder material streams:*** The value of many post-shredder material streams depends on the material purity. Inefficiencies in the current shredding and separation processes are responsible for the contaminations in post-shredder material streams. One example is copper polluting the scrap steel, which alters the properties of the melted steel. This has such a negative impact on the value of scrap steel that shredding operators in UK employ hand-pickers to remove copper wires from scrap steel (Edwards *et al.* 2006). The identification and cost effective removal of these penalty materials contaminating the post-shredder material streams before shredding can improve the value of the hulk.

- ***Inefficiencies in ad hoc applications of WEEE recovery:*** Currently there is little consistency regarding WEEE recycling due to lack of formal procedures to determine the best course of action for individual products. The recovery treatment of WEEE is mainly based on the capabilities and available resources within EEE recovery facilities. The complexity of materials contained within each product and the huge variety of products in EEE make ad hoc applications of WEEE recycling highly ineffective in terms of both ecology and economy.

The existing and future concerns in terms of legislative compliance and the increasingly competitive business environment for different stakeholders in recovery chain for WEEE highlight the need for a systematic recycling approach. The particular approach should address the identified issues to effectively maximize the recyclability of WEEE and minimise the environmental and economical impact of its recycling and disposal. To reduce the environmental impact of end-of-life EEE and increase the economic benefits of its recycling, the Recycling process planner described in the next section integrates the environmental and economic concerns to apply a holistic assessment to facilitate E&E waste recycling.

6 RECYCLING PROCESS PLANNING

The determination of eco-efficient recycling routes for WEEE is a complex problem. It involves concurrent consideration of product and process related end-of-life issues. Product related end-of-life issues involve a wide range of products with varying material composition, weight and product structure as well as the source of the product, its age and condition. Similarly, process related end-of-life issues involve a wide range of different end-of-life technologies and recycling processes, as well as their environmental and economical impacts. Therefore, to support the implementation of WEEE recovery strategies, a prototype Computer-aided recycling process planner has been developed in Visual Basic (Figure 4). Different requirements including consistency in recycling practices, availability of product recycling data and information about targeted materials/components (hazardous, valuable and contaminating materials and components) has been addressed in different stages of the recycling process planner. It is envisaged that the recycling process planning approach to producing bespoke recycling process plans for individual products in WEEE will significantly improve the end-of-life performance and eco-efficiency of recycling activities.

Figure 4, Main Menu of the Recycling Process Planner

In this approach, the generation of the recycling process plan starts with the evaluation of the product under consideration to identify the hazardous substances, valuable parts and penalty materials that need to be dismantled and removed in the initial stages. The information obtained through the product evaluation module is passed to the process planner module Then depending on the remaining material mix in the hulk, a number of shredding and separation processes are considered and assigned to recover different material streams as well as the operations required for safe disposal of remaining material. The Recycling process planner contains the database of recycling processes which have been identified through the survey of existing applications, and are grouped together in this database. Information obtained from the product evaluator module controls the recycling processes that are included

in the recycling process plan, as each product attribute is linked to one or more sub-operations in the process plan generated for an individual product. The recycling process planner also calculates and analyses the environmental impact and cost of the recycling processes through the Eco^2 Assessment module. A typical recycling process plan for a Refrigerator generated by the recycling process planner is illustrated in Figure 5.

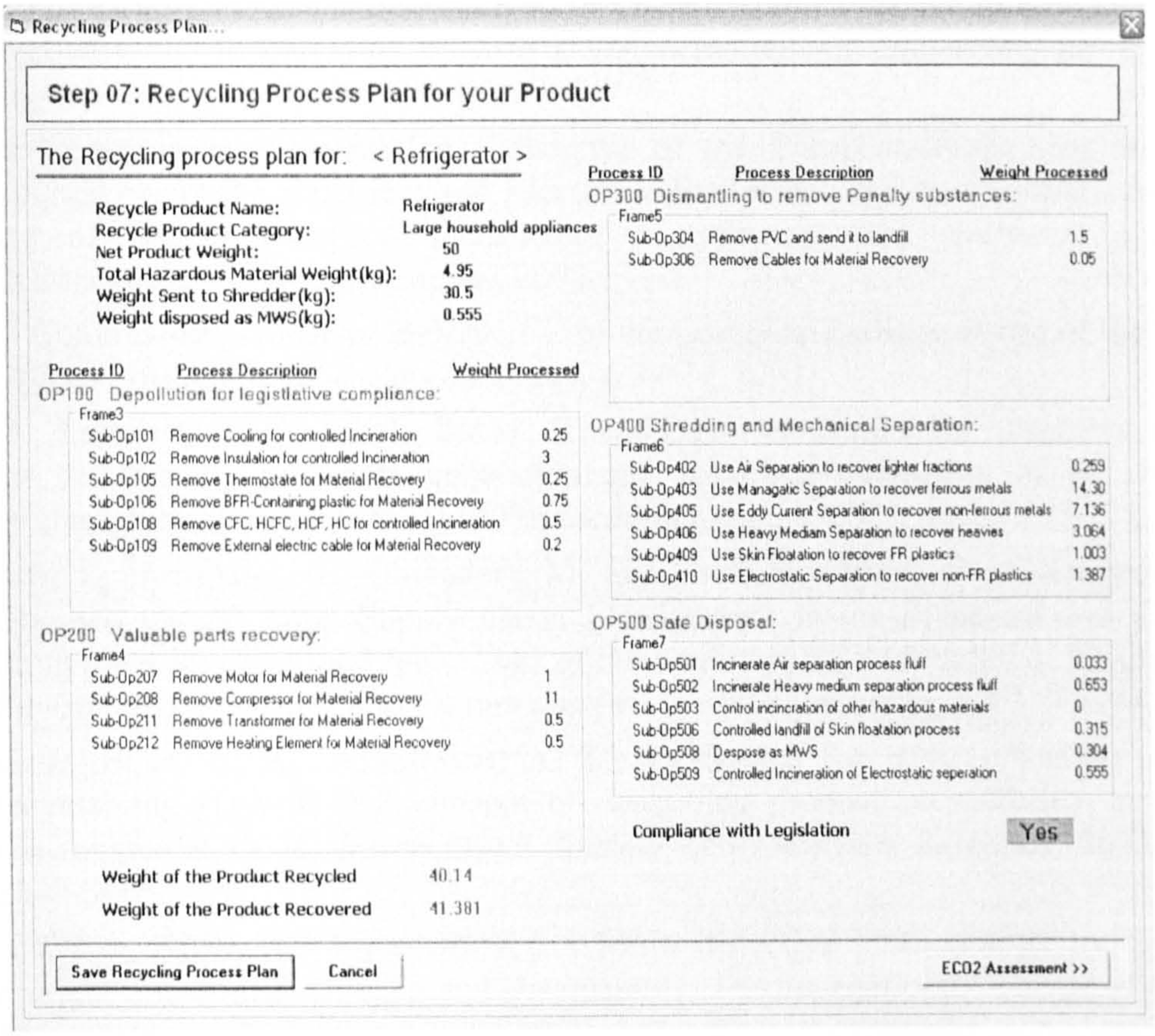

Figure 5, A Typical Recycling Process Plan for Refrigerator

7 CONCLUSIONS

Increased environmental awareness of society and upcoming producer responsibility legislation are challenging the electrical and electronics industry to reduce the environmental impacts of WEEE and associated end-of-life costs. Currently, the recovery treatment of EEE waste is mainly based on the capabilities and available resources within EEE recovery facilities, without any detailed considerations of the environmental benefits of such recycling activities. Despite the technological advances in electronics manufacturing, product recovery and recycling still remains a cost/time bottleneck in this sector and industry needs to come up with environmentally friendly and economically justifiable recycling strategies for EEE to comply with the legislation and yet at the same time to remain competitive. This paper has described an end-of-life model to improve the recyclability and value recovery from electrical and electronic waste recycling. It is argued that the adoption of a systematical approach to the generation of bespoke recycling process plans for various products is essential to address the issues hindering the current end-of-life treatment and can significantly improve the 'value recovery' and environmental performance of EEE recycling practices.

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Appendix 2

An Integrated Framework for Planning of Recycling Activities in Electrical and Electronic Sector

Introduction

This paper has been accepted for publication in the International Journal of Computer Integrated Manufacturing, December 2007.

An Integrated Framework for Planning of Recycling Activities in Electrical and Electronic Sector

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Abstract

In Europe 7.3 million tonnes of Waste Electrical and Electronic Equipment (WEEE) were created in 2002, and the fact that growth rate of WEEE is 3-5% per annum with a significant amount of this waste used to be dumped into landfills without any pre-treatment, has resulted in the introduction of European WEEE directive. The directive requires companies who manufacture or import electrical and electronic equipment to take financial and legal responsibility for its environmental-friendly recovery and recycling. The current recycling applications of WEEE are often developed on ad hoc basis and mainly attributable to the hidden economic value within used products. However, at present the recycling facilities are faced with the challenge to improve WEEE recycling activities to ensure that a larger proportion of components and materials are being recovered at a reasonable cost and yet at the same time legislative requirements are being met. A major assertion made in the research reported in this paper is that a systematic framework is needed to aid the decision making involved in adopting the best possible end-of-life strategies for WEEE. The paper presents one such integrated framework for the planning of the processes involved in the recycling of WEEE. Based on this framework a Computer-Aided Recycling Process Planning (CA*R*PP) system which generates bespoke recycling process plans for WEEE has been developed which is also described and its functionality demonstrated using a typical WEEE product.

Keywords: WEEE, Recycling Process Planning, Electrical and Electronic Equipment, Recycling

1 Introduction

Waste from electrical and electronic equipment has been identified as one of the fastest growing sources of waste in Europe (Cui and Forssberg 2003). Technological innovation and shorter product life cycles of Electrical and Electronic Equipment (EEE) coupled with its increasing use in daily life are contributing to this high rate of growth. Although it represents only 5% of the

municipal waste stream, with an average growth rate of three times greater than that of municipal waste, the quantity of WEEE is expected to double over the next decade. In addition, WEEE is non-homogenous and complex in terms of materials and components and often includes highly toxic materials such as chlorinated and brominated flame retardants, toxic metals, acids, mercury, lead and cadmium. With such hazardous elements, WEEE can cause serious environmental and health problems during disposal if not pre-treated (European Commission 2000, Macauley et al. 2003). The consumption of scarce materials in the manufacture of EEE and its disposal to scarce landfill sites along with environmental and health problems caused by WEEE have raised concerns among governments, environmentalists, manufacturers and consumers. As a result, the European Commission introduced the WEEE directive requiring producers to take responsibility for the waste management of their products. The scope of this Producer Responsibility directive targets producers, distributors, consumers and all parties involved in the treatment of WEEE and it aims to reduce the amount of WEEE going to landfills, increase reuse, recycling and other forms of recovery, and consequently reduce the environmental impacts associated with the End-of-Life (EOL) phase of EEE (European Commission 2003). In its simplest sense the directive requires EEE manufacturers to finance collection, treatment and recycling/recovery of separately collected WEEE to the specific treatment standards and meet recovery/recycling targets of 50-80% by weight depending on the type of EEE.

Historically in the UK, WEEE has either not been separately collected from other forms of waste, or it has not been properly treated prior to reprocessing (with the exception of refrigeration equipment, cathode ray tubes, and gas discharge lamps). Currently, the recovery treatment of WEEE is mainly driven by economical considerations and typically based on the capabilities and available resources within a specific EEE recovery facility, without any detailed assessment of the environmental benefits of such recycling activities. Furthermore, these recycling activities are solely focused on the reclamation of the most valuable components and materials, with a substantial amount of waste still being sent to landfill in the form of shredder residue.

The WEEE directive is impacting recycling facilities mainly in two ways. Firstly, it puts constraints on how they operate in terms of treatment and disposal of equipment to make them more environmental-friendly. Secondly, it is forcing them to develop and establish profit making opportunity from recycling of WEEE. In the wake of such legislative pressures, the recycling facilities need to improve the value recovery from WEEE recycling to ensure that a larger proportion of components and materials are being recovered from WEEE at a reasonable cost. This

highlights the need for a systematic framework to aid the decision making involved in the selection of the best possible EOL strategy for WEEE.

This paper presents one such framework to generate bespoked recycling process plans for the treatment of specific waste streams in WEEE. The initial sections of the paper present an overview of WEEE arising and outline the current shortcomings with respect to the recycling and disposal of WEEE in the UK. The latter sections present an integrated recycling process planning framework together with an associated computer-aided recycling process planner which generates the bespoke recycling process plans to improve the ecological and economical performance of WEEE recycling. Finally, the functionality of the CA*R*PP system is demonstrated through a case study of a refrigerator.

2 An overview of WEEE arising in the UK

Under the WEEE directive all EEE has been grouped into one of ten categories. Estimates of the total quantity of WEEE arising in the UK vary between 650 – 950K tonnes per year. Households provide the majority of EOL appliances. A smaller number come from appliance retailers and servicers, who typically take back old major appliances when installing new ones. A third source of used appliances is so-called "demand side management" or "early turn-in" programs where electric utilities give their customers incentives to turn in older, less efficient appliances. A report compiled by Industry Council of Electronic Equipment Recycling (ICER) based on the sales data from 2003 highlights the contribution of individual categories of equipment towards the total WEEE arising in the UK, as summarised in Table 1. Large household appliances make the largest contribution (69%) towards the weight of household WEEE, whereas in terms of number of appliances discarded small household appliances make the largest contribution (31%) (ICER 2005).

In addition to the variation in weights and numbers towards the total waste, different categories of EEE have different material compositions. For example, large household appliances consist mainly of steel (at around 61% by mass on average), whereas consumer electronic products consist largely of glass, ceramics, and plastics (at around 65%). It is therefore argued that due to this variety of materials mix and the range of routes through which WEEE may be discarded; the recycling of WEEE is more complex than the recycling of conventional materials such as steel, aluminum and paper in vehicles and packaging products. In addition, the complexity of materials contained in

WEEE does not allow a generic EOL option to be used for different products and requires initial processing and customisation of EOL recycling strategies for individual EEE products.

Table 1. Arisings of domestic WEEE in the UK in 2003 (ICER 2005)

Categories of WEEE	Tonnage discarded Tonnes (x 1000)	Per cent (Total Weight)	Units discarded (millions)	Per cent (No. of Units)
Large household appliances	644	69	14	16
Small household appliances	80	8	30	31
IT/Telecommunication equipment	68	7	21	23
Consumer equipment	120	13	12	13
Tools	23	2	5	5
Toys, leisure and sports equipment	2	<1	2	2
Lighting	2	<1	9	10
Monitoring and control equipment	<1	<1	<1	<1
Total	940	100	93	100

3 Current shortcomings in WEEE recycling

At present, a limited volume of WEEE is collected and sent to recycling facilities in the UK. The authors consider the following as some of the current shortcomings in WEEE recycling in the UK.

- ***Recovery practices driven by economical factors:*** Historically the metal dominated products (white goods) have been targeted for recycling which are often processed together with other metallic streams (like automobiles) to recover the ferrous metals. Such recycling activities have primarily been undertaken for commercial reasons to obtain the value from secondary metals without any consideration to the environmental impact of substantial quantities of waste being sent to landfill sites as shredder residues without any treatment.

- ***Lack of product data to facilitate recycling:*** Product structure and material composition information is a prerequisite for making an informed decision about selecting a recycling strategy for a particular product. However, currently in most cases access to this product

data is not available to recyclers, resulting in inconsistencies and inefficiencies in recovery treatment of WEEE.

- ***Lack of manual disassembly to recover reusable parts and materials:*** The manual disassembly of parts and materials has never been attempted by the majority of recovery facilities mainly due to the lack of awareness among recyclers about the potential value of reuse through repair and remanufacturing. Although, for the vast majority of WEEE the opportunities for environmentally justified reuse and remanufacture are very limited due to technological obsolescence and high manual dismantling cost, such end-of-life options could still provide better solution than material recycling route.

- ***Contaminations in post-shredder material streams:*** The value of many post-shredder material streams depends on the material purity. Inefficiencies in the current shredding and separation processes are responsible for the contaminations in post-shredder material streams. One example is copper polluting the scrap steel, which alters the properties of the melted steel. This has such a negative impact on the value of scrap steel that some of the shredding operators in the UK employ hand-pickers to remove copper wires from scrap steel (Edwards *et al.* 2006).

- ***Inefficiencies in ad hoc applications of WEEE recovery:*** Currently there is little consistency regarding WEEE recycling due to lack of formal procedures to determine the best course of action for individual products. The recovery treatment of WEEE is mainly based on the capabilities and available resources within a specific recovery facility. The complexity of materials contained within each product and the huge variety of products in EEE, make ad hoc applications of WEEE recycling highly ineffective in terms of both ecological and economical considerations.

The existing and future concerns in terms of legislative compliance together with the competitive business environment for different stakeholders in WEEE recovery chain highlight the need for a systematic and a more efficient recycling approach which addresses the shortcomings identified above to effectively maximise the recyclability of WEEE and minimise the environmental and economical impacts of its recycling and disposal.

4 A brief review of most relevant research

An overview of EOL planning problems in a product life cycle are given by Gungor and Gupta (1999), Fleischmann *et al.* (1997) and Goggin and Browne (1998). For product recovery and recycling, several decision factors should be considered when determining the maximum environmental benefits that can be achieved for a given economic cost when a product reaches its EOL. These factors include the level of disassembly, sequencing for dismantling operations, the EOL routes for removed components as well as the hulk and the reverse logistics. A number of previous investigations have considered important aspects of recovery optimisation problem. For instance, Johnson and Wang (1998) present a systematic procedure of generating the best disassembly sequence to maximise the profits of material recovery. Penev and de Ron (1996) describe a cost modelling tool to determine an economical disassembly level and disassembly sequence for a specific product. Goggin and Browne (2000a) describe a software model for the decision-support to identify the most favorable route from a cost and value perspective. Lambert (1997) develops a linear optimisation model for an optimum disassembly of complex products. Pnueli and Zussman (1997) suggest a dynamic programming algorithm to solve the disassembly sequencing problem that includes the EOL value of a product.

Remanufacturing represents a higher form of reuse by focusing on environmentally value-added recovery, rather than materials recovery and recycling which have its own disadvantages and environmental impacts. Guide (2000) presents a survey of production planning and control activities at remanufacturing firms and claims that significant changes in production planning and control activities are needed for their use in remanufacturing facilities. Clegg *et al.* (1995) present linear programming models of production systems with remanufacturing capability to examine the effects of different cost structures on the long-term viability of remanufacturing operations. Ferguson and Browne (2001) examine information requirements for reverse logistics within the Extended Enterprise.

Some studies have incorporated both cost estimation and environmental impact estimation. For example, Krikke *et al.* (1998) describe a method on a tactical management level to determine the best recovery and disposal strategy of product type considering technical, economical and ecological criteria. Lee *et al.* (2001) try to find alternative that can both maximises profit and minimises environmental impact and use a coffee maker as an example. Yu *et al.* (2000) adopt

analytical hierarchic process to find the best recycling strategy in which environmental impact, cost and reclaimed materials were considered as the major criteria for strategy selection. Huisman *et al.* (2003) describe 'the quotes for the environmentally weighted recyclability' or QWERTY approach which focuses on the determination of environmentally weighted recycling scores. Herrmann et al. (2002) describe a method to calculate economical and ecological indicators to evaluate EEE waste in regards to material recycling, and used life cycle assessment and life cycle costing to calculate these indicators.

The recent publications that deal with decision-support systems for WEEE recycling mainly provide the assessment on macro level. For example, Lamvik *et al.* (2002) present the AEOLOS methodology to determine the most appropriate EOL option (reuse, material recycling, incineration or disposal) based on economic, environmental and societal criteria. Rose *et al.* (1999) present a design oriented decision framework which focuses on technical product design variables such as expected life time and number of parts to select an appropriate EOL strategy at the design stage. On the other hand, Goggin and Browne (2000b) describe a taxonomy of electrical and electronic manufacturing situations from a resource recovery perspective to provide an understanding of the recovery and recycling issues. The framework presented in this paper is unique in that it explores multi-objective optimization for generation of process plans for recycling activities. The framework further extends previous research in EOL decision-support systems by considering best possible sets of trade-offs between environmental and economical variables and includes simultaneous consideration of the macro level EOL planning (product reuse, material recycling, disposal) and micro level EOL planning (pre-treatment and depollution, removal of valuable parts and penalty materials, shredding and separation processes).

5 An integrated framework for WEEE recycling

An EOL product may be discarded to landfill, incinerated, disassembled for material reclamation, collected and examined for possible refurbishment and reuse, or indeed a combination of these activities may occur. Each EOL option incurs economical and environmental costs and creates potential value. There are many factors that influence the selection of the most appropriate EOL strategy including environmental impact, legislative compliance, market competition, as well as the impact on brand image, product design complexity and material composition. The integrated recycling process planning framework presented in this paper aims to assist designers,

manufacturers and EEE recycling facilities in determining the bespoked end-of-life recycling process route for an individual product (or product family) in WEEE. It is argued that such systematic approach to developing a bespoke recycling process plan minimises the environmental impacts of EOL management in a technically feasible way and at a reasonable cost. Figure 1 provides an overview of the various stages of the Recycling Process Planning (RPP) framework.

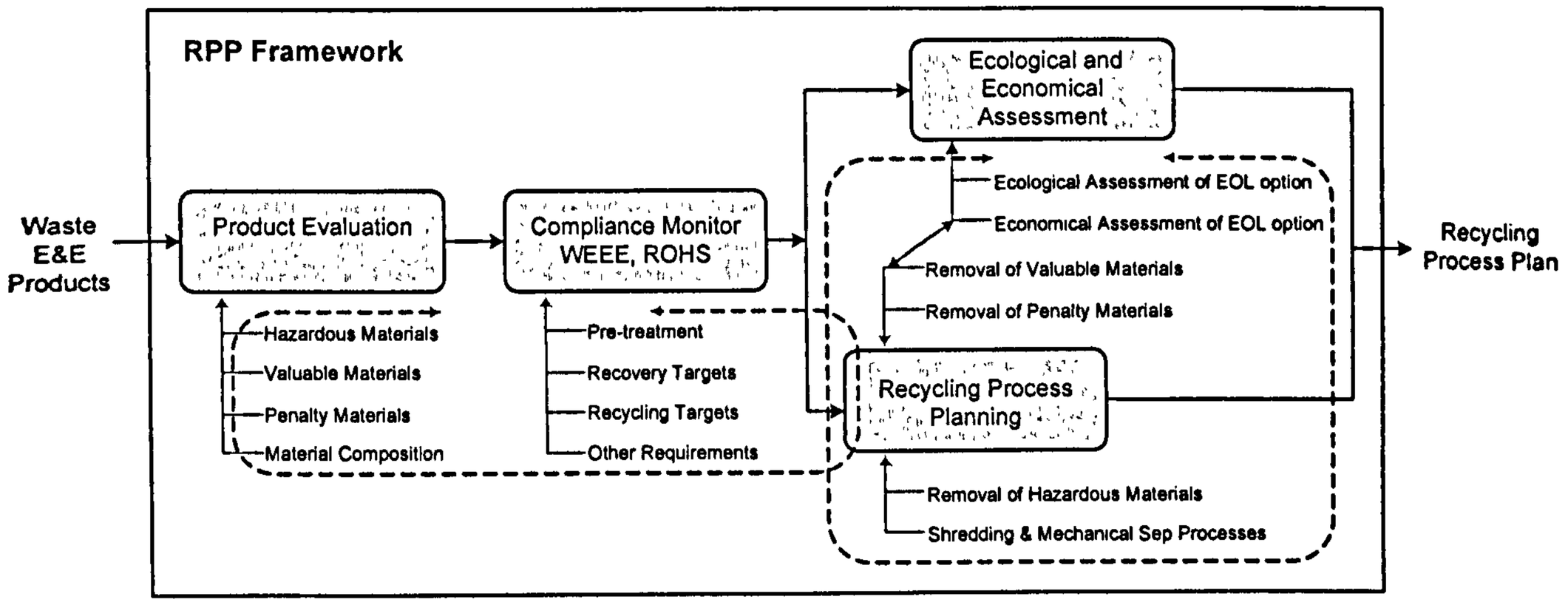


Fig 1. Stages in the recycling process planning framework

The activities within the RPP framework begin with the product evaluation stage to identify the components of interest and the material composition within the product (see Figure 2). This product information is then used to identify the various requirements for legislative compliance and specific pre-treatment processes. Subsequently, a recycling process planning stage identifies the specific product recovery and recycling processes to suit a particular EEE product scenario. Finally the Ecological and Economical (Eco2) assessment stage analyses the environmental and economical impacts associated with the EOL processes proposed by the RPP framework. The tasks involved in each stage of the RPP framework are described in more detail below.

5.1 Product evaluation

The first stage of the RPP framework, namely the product evaluation, identifies the main design and material characteristics of the product. Product evaluation is needed to classify the product into a particular WEEE category according to Annex 1A of the WEEE directive and to identify the crucial factors that determine the selection of a recovery option. There are four main tasks involved in product evaluation.

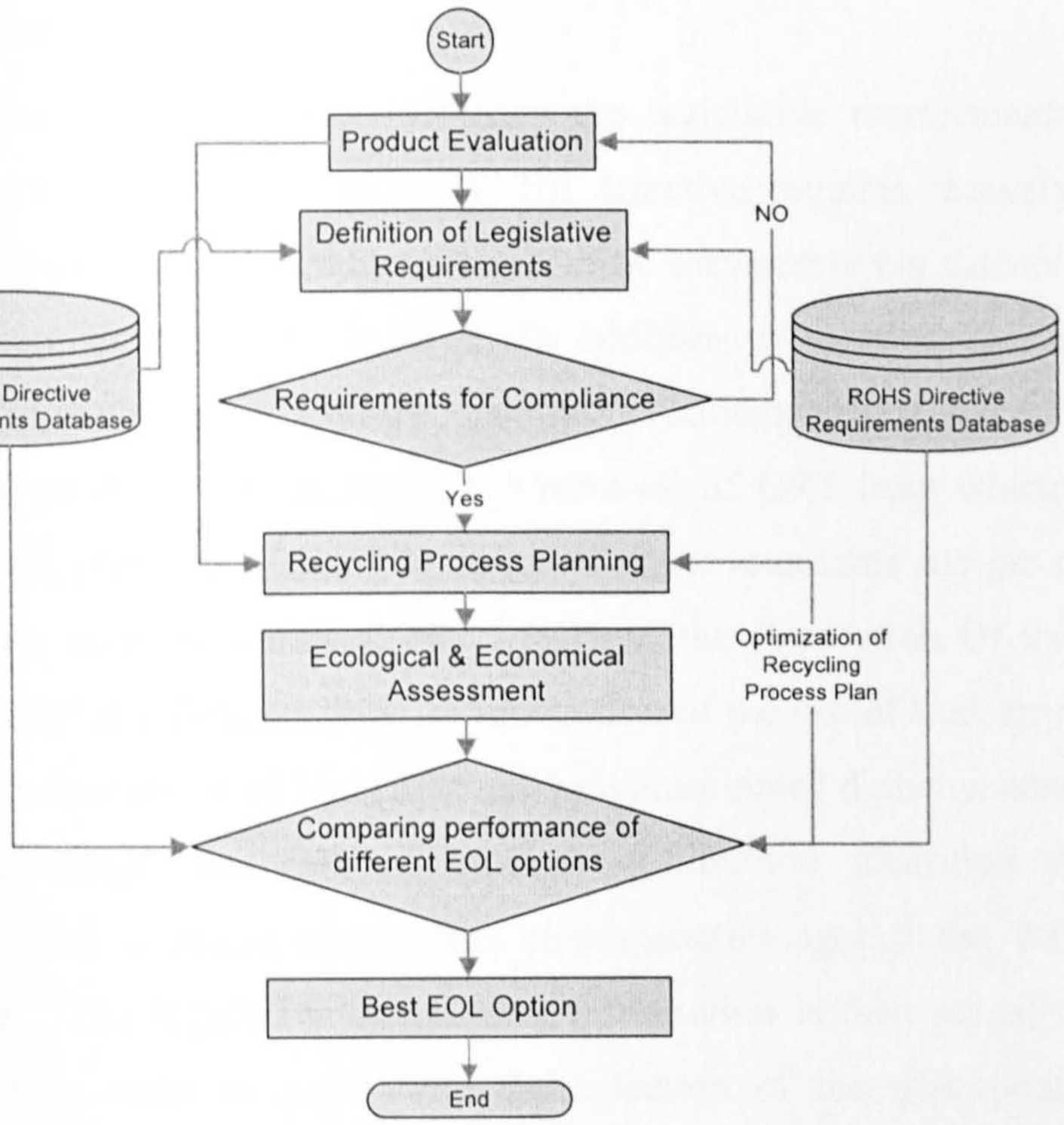


Fig 2. The tasks involved in the generation of recycling process plans

The first task determines the hazardous and toxic substances present in the product. This evaluation is essential for the selection of appropriate pre-treatment processes in order to comply with the requirements of Annex 1B of the WEEE directive related to the treatment of hazardous materials. The second and third tasks determine the valuable/reusable components and penalty (contaminating) materials in the product. Removal of valuable and reusable components before destructive disassembly can also improve the eco-efficiency of the product recycling provided that the environmental gain from this disassembly overweighs removal cost. Similarly, removal of penalty materials can improve the value of the hulk. For example, removal of copper wires improves the value of the scrap steel. Finally in the fourth task, material composition of the product is identified and the product hulk is divided into material streams like ferrous metals, non ferrous metals, plastics, glass etc. Based on this material composition appropriate shredding and mechanical separation processes are assigned. The information collected and processed as part of the product evaluation stage is used to support the remaining stages in the RPP framework as outlined below.

5.2 Legislative compliance monitoring

The second stage of the RPP framework identifies the legislative requirements related to the recycling of the product under consideration. WEEE directive requires recovery and recycling targets ranging from 50% to 80% by product weight to be met across ten categories of electrical and electronic equipment as shown in Table 2. In addition to meeting certain recovery and recycling targets, the directive also requires specific treatment and recovery methods to be followed for individual products. For example, the removal of CRT from which the fluorescent coating must be removed, plastic containing brominated flame retardants and gas discharge lamps from which the mercury must be removed etc. Similarly, the Restriction Of the use of certain Hazardous Substances (RoHS) directive requires prevention of the use of lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ether in EEE. In the compliance monitoring stage, the detailed product information identified through product evaluation stage is utilised to assess the product characteristics against the WEEE and ROHS directives requirements. The legislative compliance information is then passed to the recycling process planning stage in order to assist with the selection of the appropriate recovery and recycling processes.

Table 2. Recovery and Recycling Targets for WEEE

Categories of WEEE	Minimum Targets by average weight per appliance	
	Recovery	Recycling and Reuse
Large household appliances	80%	75%
Small household appliances	70%	50%
IT/Telecommunication equipment	75%	65%
Consumer equipment	75%	65%
Lighting equipment	70%	50%
Electrical and Electronic tools	70%	50%
Toys, leisure and sports equipment	70%	50%
Medical appliances	No Targets	
Monitoring and control equipment	70%	50%
Automatic dispensers	80%	75%

5.3 Recycling process planning

The third stage of the RPP framework generates bespoked recycling process plans for an individual EEE product. The recycling process planning stage aims to take advantage of the benefits provided by a systematic approach to process planning experienced in manufacturing applications (Marri *et al.* 1998) and apply a similar principle to increase the efficiency of recycling activities. There are two basic approaches to process planning, namely generative and variant approach. The generative approach to process planning is based on developing a completely new plan for every product (or its parts and components). It uses the decision logic, formulae, algorithms and geometric analysis and is considered to be more suitable for developing process plans for complex and novel product designs. On the other hand in the variant approach to process planning, a standard plan is modified to suit the given product. The standard plan is usually developed for a complex product that incorporates all the features of a particular group or family of products. The process plan for product under consideration is compiled by retrieving those sections of the standard plan that are relevant.

In case of recycling process planning of WEEE, nature and range of processes are not as complicated as in manufacturing and do not require generation of completely new plans (as in generative approach) for different materials and components in WEEE. In addition, there is a huge potential for the reuse of subsets of the recycling process plans among WEEE due to the inherent parts and products commonality between different EEE products. Hence, the adaptability and flexibility offered through variant approach justify its application for the recycling process planning. In the RPP framework based on the product categories used in the WEEE directive, a number of standard recycling process plans have been developed and used for generation of bespoke recycling process plans for individual products. The generation of the standard recycling process plans is supported by a central database consisting of a list of all contemporary recycling processes used in WEEE recycling and their associated environmental and economical impacts. A standard recycling process plan for a specific category of EEE consists of a wide range of recovery and recycling processes to cater for the variety of electrical and electronic products in that category together with broad range of components and substantial differences in material composition among those products. It is claimed that the utilisation of the variant approach to recycling process planning allows for the adoption of different EOL strategies (reuse, refurbishment, material recycling, incineration and disposal) for different components and materials contained in a product to improve the overall performance of WEEE recycling.

5.4 Ecological and economical assessment

The final stage of the RPP framework is the Eco2 assessment which compares the environmental and economical impacts of various EOL options for WEEE. This assessment is important in order to determine the best EOL route for specific product and to prioritise the recovery and recycling processes based on their eco-efficiency. The Eco-Indicator 99 methodology (PRE Consultants 2000), which is a damage oriented life cycle assessment method, has been used to calculate the environmental impacts associated with each EOL process. In this methodology all environmental effects are translated to actual damage inflicted to eco-system quality, human health and resource depletion. Human health and ecosystem quality are considered to be of almost equal importance, while resources are considered to be half as important. The final result in this methodology is expressed in a single score (i.e. a point) that indicates the overall damage to the environment and is easier to interpret than the conventional LCA results. In the Eco-Indicator 99 methodology, one point is representative for one thousandth of the yearly environmental load of one average European inhabitant. Based on this methodology, an upper and lower limit of environmental impact is calculated as part of Eco2 assessment to provide a scale for the evaluation of the actual environmental impacts associated with a specific recycling process plan. The upper limit of environmental performance is based on the assumption that all materials can be recovered (zero landfilling) without any environmental burden whereas the lower limit of environmental performance assumes all materials in the product will end up in the landfill. Provisions are made for the material degradations and process inefficiencies to be considered while calculating the actual environmental impacts associated with a recycling process plan and with other EOL options.

A parametric cost modelling approach is used to calculate the economical impacts associated with product recycling. All respective EOL processes are quantified according to the different costs, e.g. disassembly cost, processing cost, disposal cost and material revenues, and by summing up all the relevant costs and revenues, the actual economical performance is calculated. An upper (best case scenario) limit of economical performance related to 100% recovery and recycling of all material contents and a lower (worst case scenario) limit of economical performance related to the cost of sending the complete product to landfill are defined and used to evaluate the actual economical performance of different recycling process plans. Finally, the eco-efficiency of different EOL options, which is a ratio of environmental benefit to unit cost, is calculated to aid the decision making involved in selecting the most suitable end-of-life processes for WEEE.

6 A Computer-Aided Recycling Process Planner

The generation of the above-mentioned eco-efficient recycling process plans for WEEE is a complex task which involves concurrent consideration of product and process data related to a wide range of EOL issues such as varying material composition, weight and product structure, product age and condition, various recycling processes and technologies and their environmental and economical impacts. This requires a significant amount of data processing and decision making. Therefore, a Computer-Aided Recycling Process Planning (CA***R***PP) system is developed based on the RPP framework described in Section 5. The CA***R***PP system consists of a user interface module, a database module, a recycling process planning module and an assessment module as shown in Figure 3.

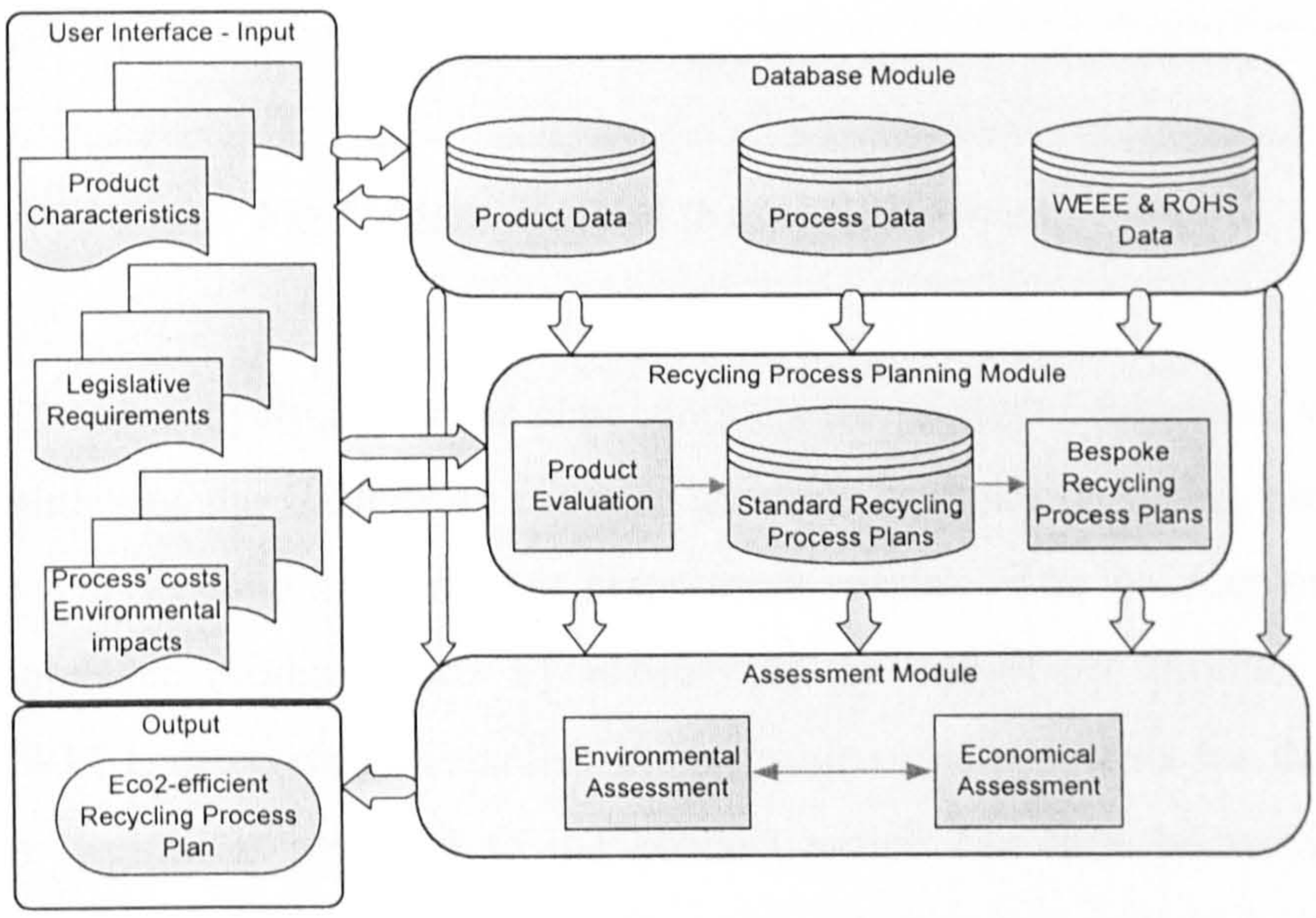


Fig 3. Architecture of the CARPP system

The user interface module receives and controls the user input and gives access to the CA***R***PP output. The interface has been developed in Microsoft Visual Basic 6 and integrated with Microsoft Access (used to develop the Database module). The main menu of the user interface module (shown in Figure 4) is split into three parts, namely the generation of a new recycling process plan, the environmental assessment of a recycling process plan, and the economical assessment of a recycling process plan.

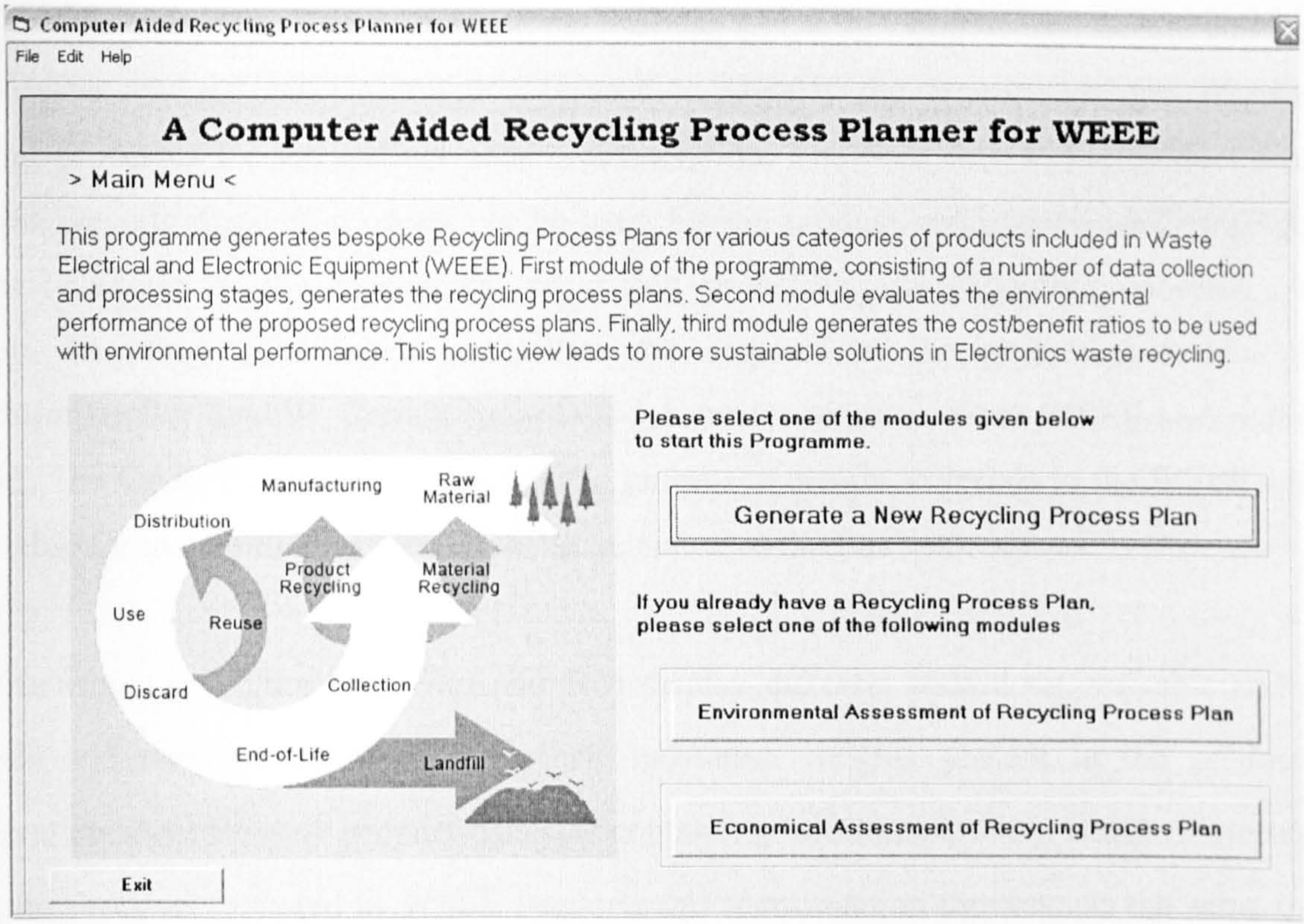


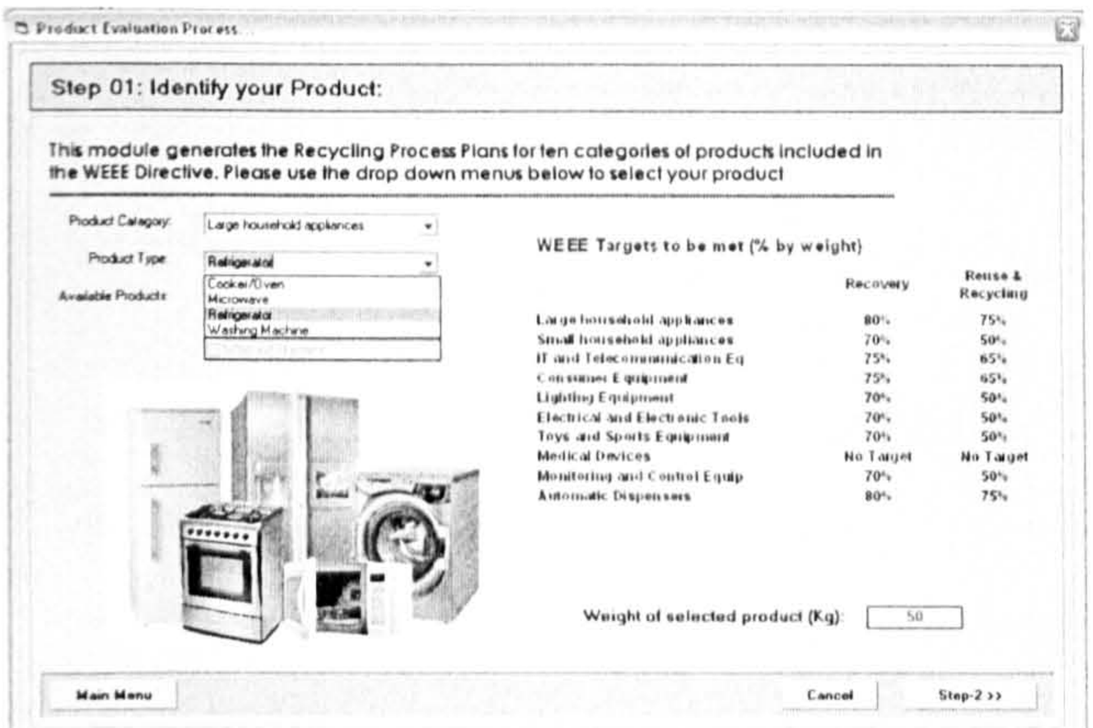
Fig 4. Main menu of the CARPP system

The generation of a new recycling process plan conducts the product evaluation, which can then be used by other modules of the CA***R***PP in order to generate bespoke recycling process plans along with the ecological and economical impact assessment results. The product evaluation process within the user interface module starts by identifying the end-of-life product and its category according to the WEEE directive to establish the legislative requirements for the product (Figure 5a). An indicative weight is assigned to the product which can then be used to calculate the recovery and recycling targets for the product. Once a product is selected, the user is then asked to confirm the hazardous and toxic substances present in the product (Figure 5b). These identified hazardous and toxic substances trigger the appropriate pre-treatment processes to be included in the product's bespoke recycling process plan. The third evaluation task within the user interface module identifies the valuable materials and components present in the product (Figure 5c). In order to improve the value of post fragmentation material streams, the product evaluation process identifies the penalty materials and components present in the product to be removed before sending the product to fragmentation process (Figure 5d). Once the information about various hazardous, valuable and penalty materials included in the product is collected, material composition of the product is identified and the product hulk is divided into different material streams such as ferrous/non-ferrous metals, plastics, glass etc (Figure 5e). This distribution is based

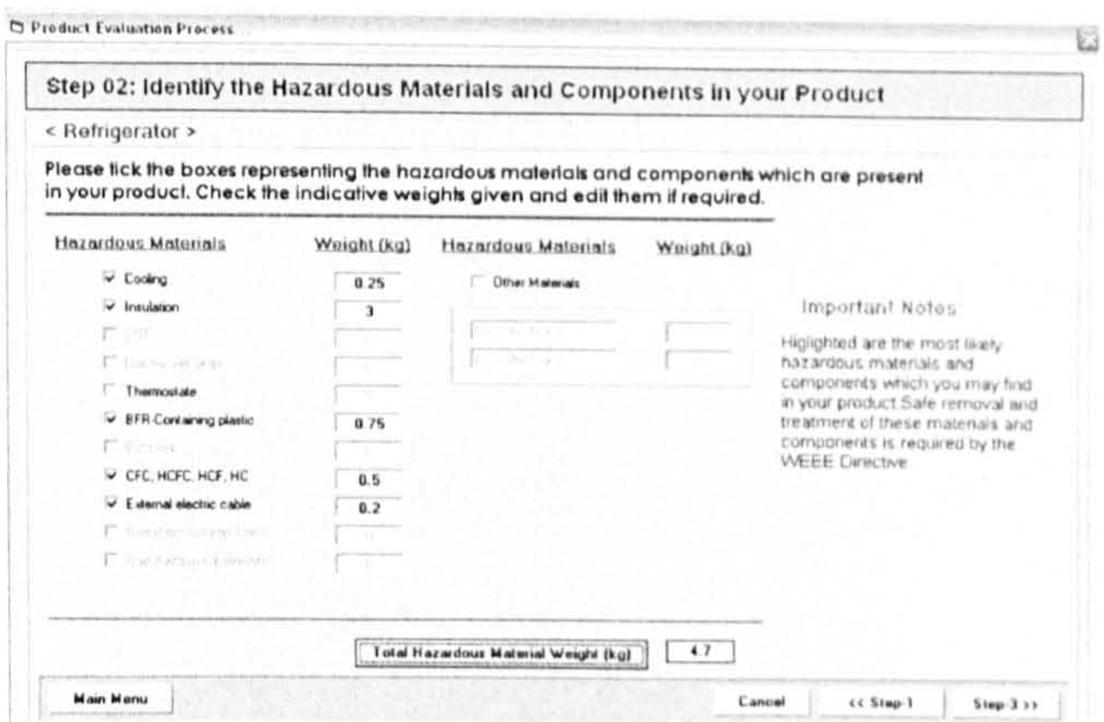
on the generic composition of WEEE and the user can adjust the composition data to suit a specific product. The material mix information is used to identify the appropriate post fragmentation recycling processes for the product under consideration. The final task in the product evaluation identifies the safe disposal processes to be used for the product under consideration (Figure 5f). The inefficiencies of the mechanical separation processes and economic concerns over the available recycling technologies necessitate the disposal of the remaining residue through incineration and/or landfill. Certain hazardous substances removed from WEEE also require safe disposal. The CA*R*PP is able to assign landfill process to certain materials in the WEEE which are not suitable for incineration in view of the toxic nature of the flue gas residues.

The screenshots in Figure 5(b), 5(c) and 5(d) display different hazardous, valuable and penalty materials and components along with their indicative weights present in the product under consideration. An extensive product database containing information about different electrical and electronic products included in WEEE supports this identification process. At the same time, the user interface of the CA*R*PP provides users with a manual data input option for additional materials and components of interest which have not been included in the database. Furthermore, it allows users to alter the indicative weights of proposed materials and components.

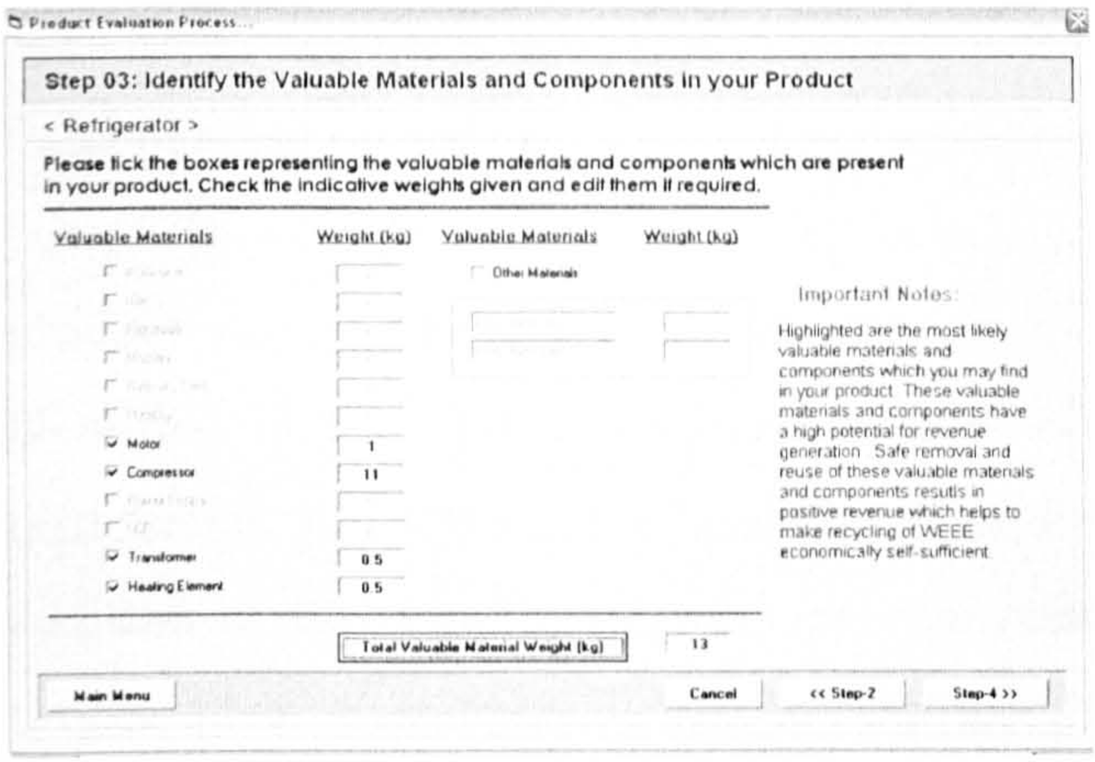
The information obtained through the user interface is passed to the database module and the recycling process planning module. The database module stores a variety of different EOL information (e.g. product data, process data and legislative requirements data) and provides access to this information to other modules in the CA*R*PP system. Any new product information obtained during product evaluation is also added to the respective database within the database module. The product database contains information about product characteristics, its WEEE category, weight, material composition and components. The process database consists of a list of all contemporary recycling processes used in WEEE recycling and their associated environmental and economical impacts including environmental impacts for material recycling, incineration and landfill as well as dismantling times and costs, processing costs, disposal costs and material revenues. The legislation database contains information about WEEE and ROHS directive and includes recovery targets, recycling targets and pre-treatment requirements.



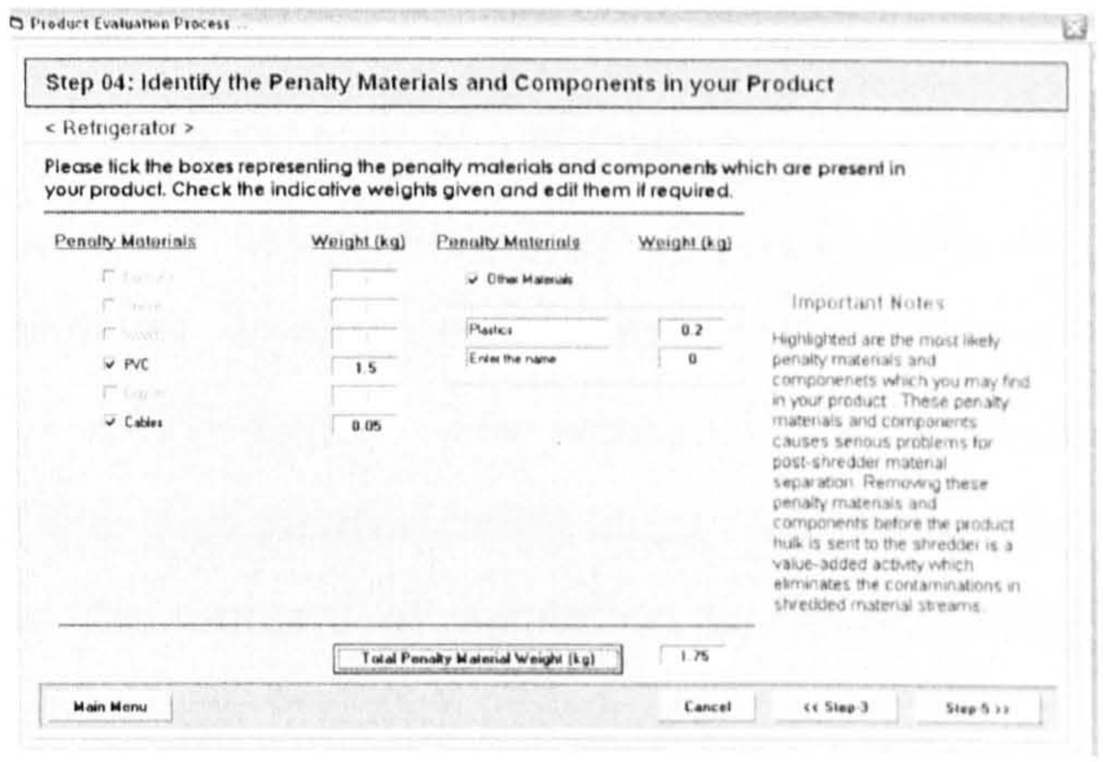
(a) Product identification stage



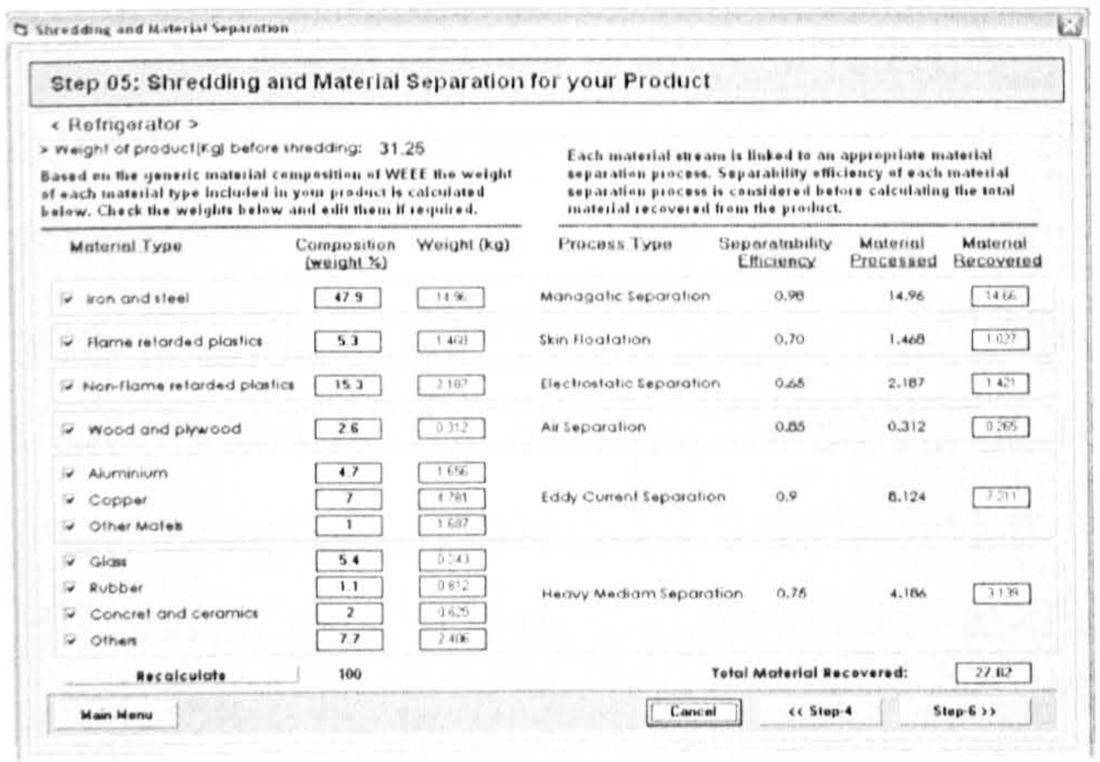
(b) Hazardous materials identification stage



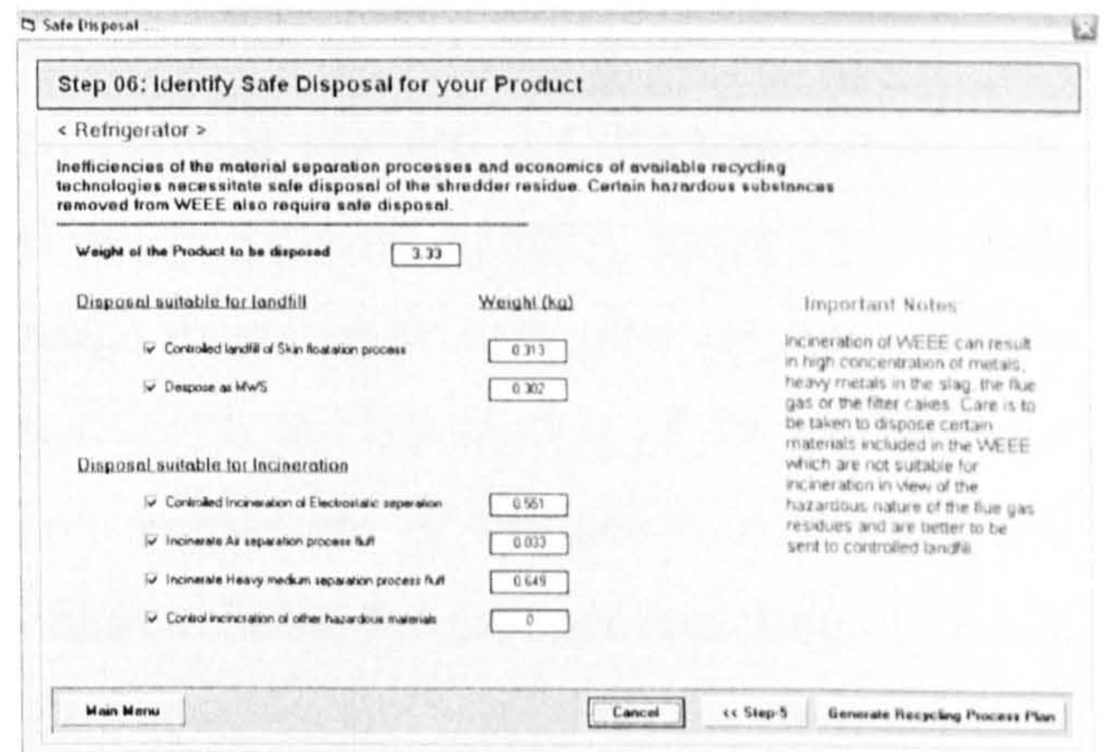
(c) Valuable materials identification stage



(d) Penalty materials identification stage



(e) Mechanical separation identification stage



(f) Safe disposal identification stage

Fig 5. User interface module of the CARPP system

The recycling process planning module generates the bespoked recycling process plans for WEEE, and it is based on a central database which is linked to the other modules of the CA***R***PP. The central database contains standard recycling process plans for different categories of electrical and electronic products included in WEEE. The information obtained through the product evaluation is used within the recycling process planning module to customize the appropriate standard recycling

process plan into a bespoke recycling process plan based on a variant approach to process planning (see section 5.3). The standard recycling process plan consists of the following five main categories of operations:

- De pollution for legislative compliance
- Dismantling for value recovery
- Dismantling to remove penalty substances
- Shredding and mechanical separation to recover different material streams
- Disposal / Landfill

Each of these operation categories in recycling process plans consists of a number of relevant sub-operations i.e. specific recovery and recycling processes. These processes are linked to different product design and material characteristics, as well as legislative compliance requirements identified in the first and second module of the CA*R*PP system. For example in case of a refrigerator, the presence of insulation identified during product evaluation stage will trigger the addition of the specific recovery process related to the removal of insulation in the recycling process plan. A typical recycling process plan for a refrigerator is shown in Figure 6.

The Eco2 assessment module of the CA*R*PP system provides an insight to environmental and economical impacts of a recycling process plan, before it is selected for implementation. The assessment module generally considers three end-of-life options namely, recycling through shredding (current recycling practice), recycling through recycling process plan (as suggested by CA*R*PP) and landfilling. The assessment process starts with the calculation of the performance limits which provide a scale for the evaluation and assessment of the actual ecological and economical performance of different end-of-life options available for product recycling. It should be noted that the upper performance limit is the best case scenario and represents the environmental gain (usually a negative Eco-Indicator 99 value) related to the use of recycled rather than virgin material. The lower limit is the worst case scenario (usually a positive Eco-Indicator 99 value) and represents the environmental burden related to sending the complete product to landfill. Figure 7 presents the calculation of the upper and lower limit of environmental performance for the refrigerator.

Recycling Process Plan...

Step 07: Recycling Process Plan for your Product

The Recycling process plan for: < Refrigerator >

Recycle Product Name:	Refrigerator
Recycle Product Category:	Large household appliances
Net Product Weight:	50
Total Hazardous Material Weight(kg):	5.2
Weight Sent to Shredder(kg):	30.8
Weight disposed as MWS(kg):	0.560

OP100 Depollution for legistlative compliance:

Process ID	Process Description	Weight Processed
Sub-Op101	Remove Cooling for controlled Incineration	0.25
Sub-Op102	Remove Insulation for controlled Incineration	3
Sub-Op105	Remove Thermostate for Material Recovery	0.25
Sub-Op106	Remove BFR-Containing plastic for Material Recovery	1
Sub-Op108	Remove CFC, HCFC, HCF, HC for controlled Incineration	0.5
Sub-Op109	Remove External electric cable for Material Recovery	0.2

OP200 Valuable parts recovery:

Process ID	Process Description	Weight Processed
Sub-Op207	Remove Motor for Material Recovery	1
Sub-Op208	Remove Compressor for Material Recovery	11
Sub-Op211	Remove Transformer for Material Recovery	0.5
Sub-Op212	Remove Heating Element for Material Recovery	0.5

Weight of the Product Recycled	40.42
Weight of the Product Recovered	41.673

OP300 Dismantling to remove Penalty substances:

Process ID	Process Description	Weight Processed
Sub-Op304	Remove PVC and send it to landfill	1.5
Sub-Op306	Remove Cables for Material Recovery	0.05

OP400 Shredding and Mechanical Separation:

Process ID	Process Description	Weight Processed
Sub-Op402	Use Air Separation to recover lighter fractions	0.261
Sub-Op403	Use Managatic Separation to recover ferrous metals	14.45
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	7.206
Sub-Op406	Use Heavy Mediam Separation to recover heavies	3.093
Sub-Op409	Use Skin Floatation to recover FR plastics	1.012
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	1.401

OP500 Safe Disposal:

Process ID	Process Description	Weight Processed
Sub-Op501	Incinerate Air separation process fluff	0.033
Sub-Op502	Incinerate Heavy medium separation process fluff	0.66
Sub-Op503	Controlled incincration of other hazardous materials	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.318
Sub-Op508	Dispose the waste as MWS	0.307
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.560

Compliance Monitor

Refrigerator	Recovery (%)	Recycling (%)
Targets	80	75
Achieved	83.35	80.84
Compliance	Yes	Yes

Exit | Save Recycling Process Plan | ECO2 Assessment >>

Figure 6. A typical recycling process plan for Refrigerator

The actual environmental performance of a recycling process plan is calculated by considering the impact of each individual recycling process included in the plan. Material weights and grades and their EOL destinations as well as the process efficiencies of separation processes are considered while calculating the actual environmental performance of the recycling processes. Figure 8(a) depicts the environmental impact assessment of the recycling process plan for the refrigerator. The second part of the Eco2 assessment module enables the economical assessment of the recycling process plan. In a similar way, an upper and lower economical performance limit are defined before calculating the actual economical impacts of different EOL options. Data about the costs and revenues (negative cost) of different recovery and recycling processes is retrieved from the database module. Figure 8(b) depicts the calculation of the economical impact of the current recycling practice for the refrigerator.

ECO2 Assessment...

Step 1: Environmental Assessment of your Product's End-of-Life

< Refrigerator >

Upper and Lower Limits of Environmental Performance for Refrigerator

Recycle Product Name: Refrigerator **Net Product Weight:** 50

An upper and lower limit of EOL Environmental Performance (EI,u and EI,l respectively) is calculated to evaluate the environmental performance of the proposed RPP.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg)		mi x Eln subst (mPt)	mi x Eln eol,L (mPt)
		Material Substitution (Eln subst)	Landfill (Eln eol,L)		
Steel	23.95	-86	1.4	-2059.7	33.53
FR Plastics	2.65	-383.3	3.95	-1015.74	10.47
NFR Plastics	7.65	-383.3	3.95	-2932.25	30.22
Wood / Plywood	1.3	-39	4.2	-50.7	5.46
Aluminium	2.35	-780	1.4	-1833	3.29
Copper	3.5	-1400	1.4	-4900	4.9
Other matels	0.5	-1150.9	1.4	-575.45	0.7
Glass	2.7	-66	1.4	-178.2	3.78
Rubber	0.55	-360	7.4	-198	4.07
Concrete	1	-3.8	1.4	-3.8	1.4
Others	3.85	-100	1.4	-385	5.39

Upper limit of Environmental Performance = mi x Eln subst = -14131.84

Lower limit of Environmental Performance = mi x Eln eol,L = 103.21

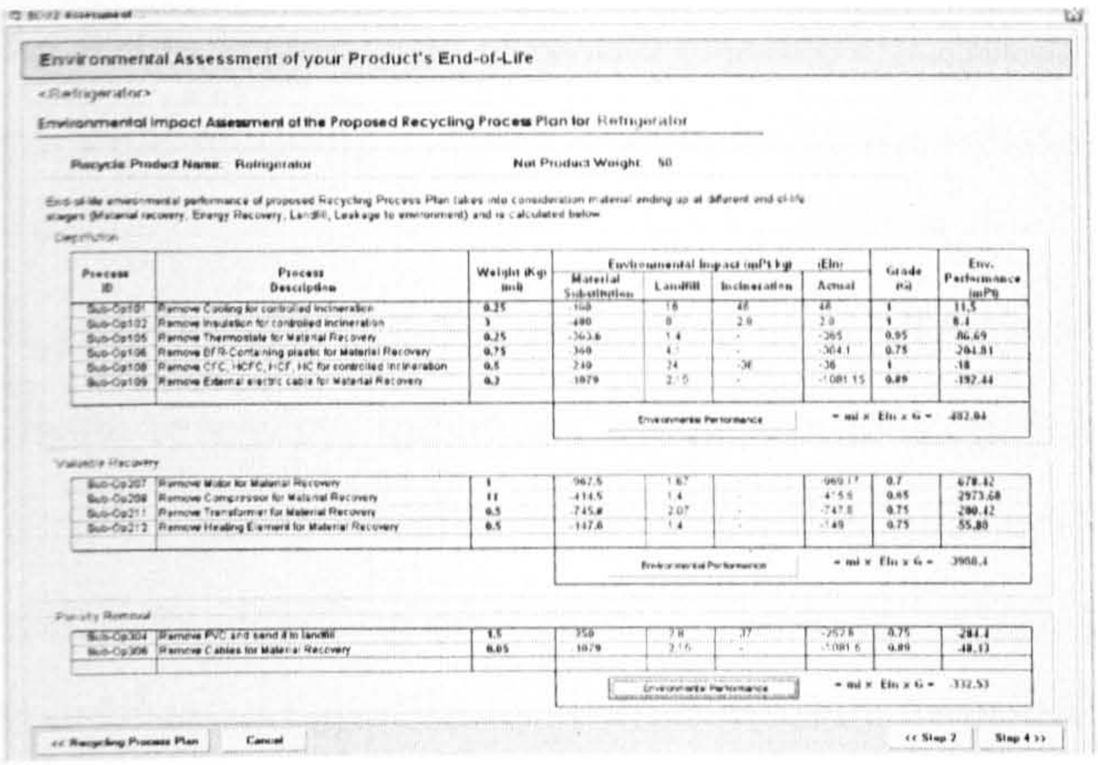
Upper limit of environmental performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any environmental burden of treatment processes."

Lower limit of environmental performance is calaculated considering that every material in the Product is ending up in the landfill without any environmental burden of treatment processes."

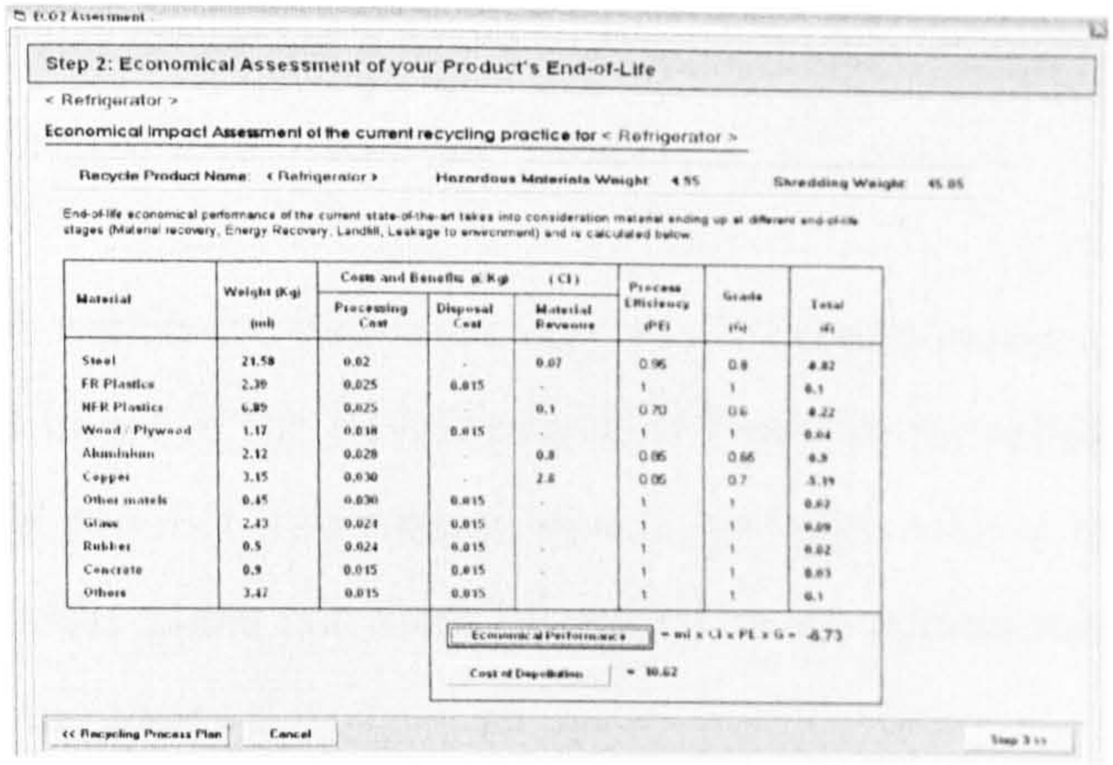
<< Recycling Process Plan | Cancel | Step 2 >>

Fig 7. Environmental performance limits for Refrigerator recycling

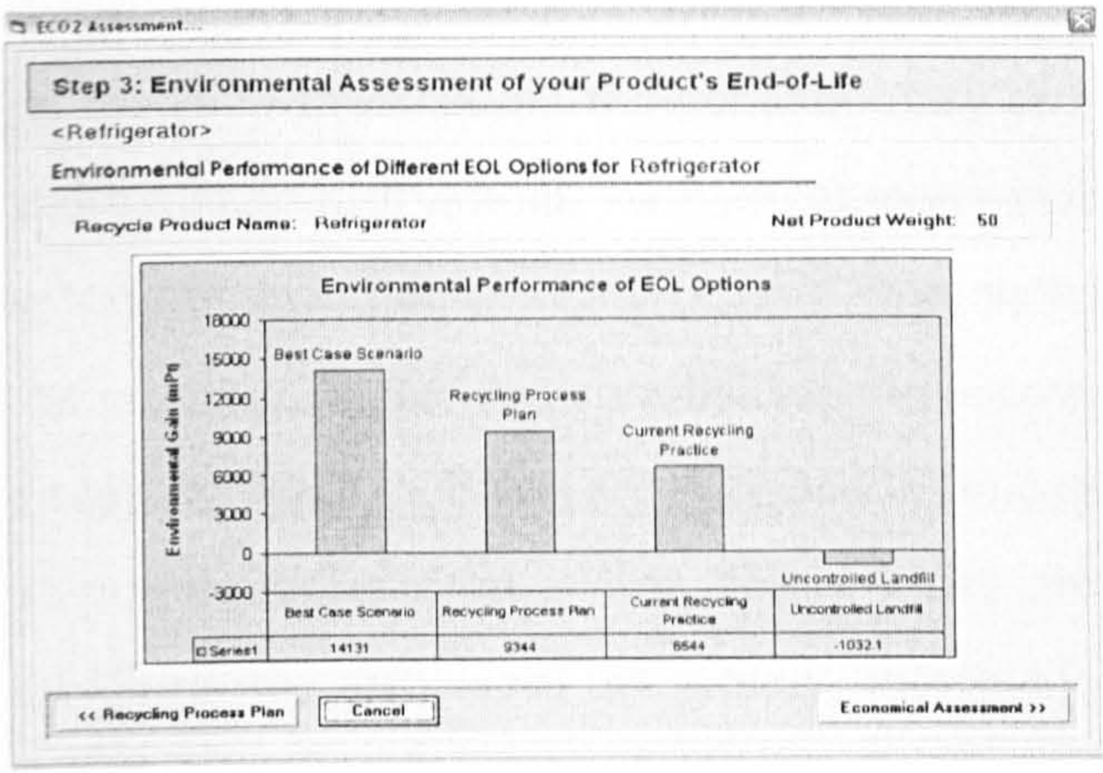
Finally, the environmental and the economical performance measures are combined to calculate the eco-efficiency, which is a ratio of environmental benefit to unit cost involved. The eco-efficiency scores for different EOL options for a refrigerator are plotted on a two-dimensional environment-cost diagram (Figure 8d). This eco-efficiency diagram clearly highlights the significant environmental and economical impacts of landfilling option in comparison to the current practices and the end-of-life options included in the bespoke recycling process plan generated for the refrigerator. Furthermore, the eco-efficiency diagram also underline the substantial improvement that could be achieved in the environmental and economical performance of WEEE recycling activities through adoption of a systematical approach for generation of a recycling process plan based on the most up-to-date information and knowledge on recycling processes, contained within the CA***R***PP. Finally, the authors argue that though the CA***R***PP is currently developed for the application of WEEE recycling, the underlying principal could easily be reapplied for various manufacturing sectors with complex end-of-life management options for their post-consumer waste.



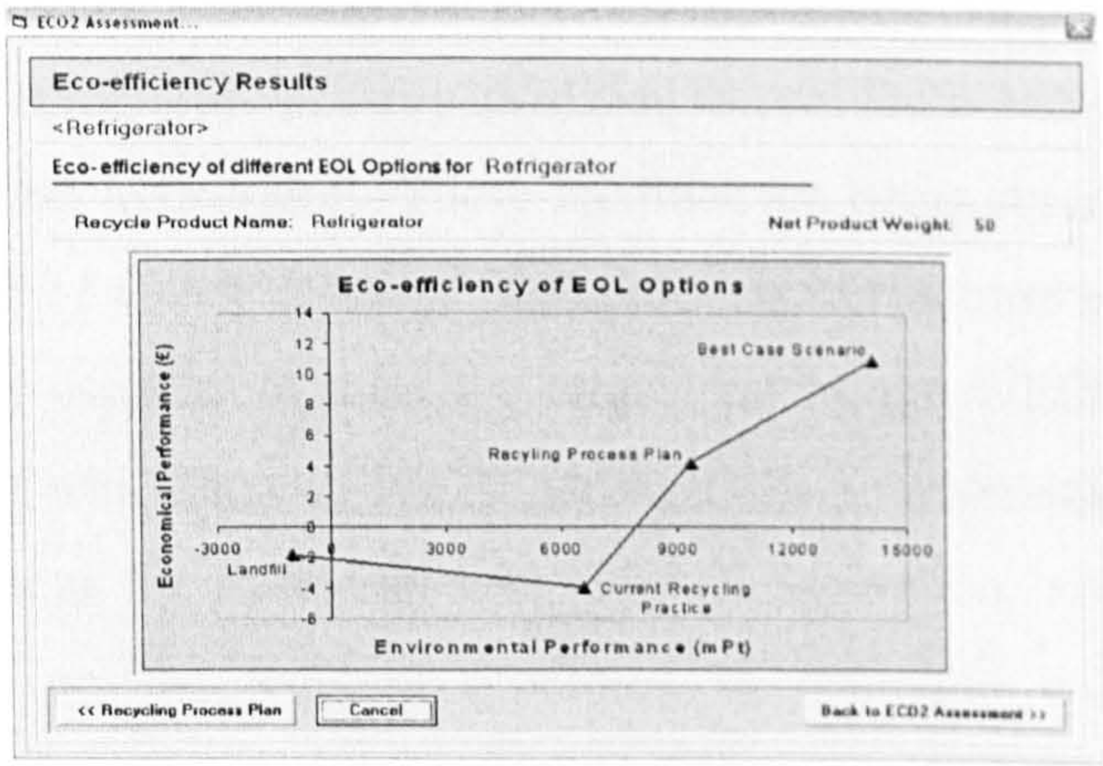
(a) Environmental assessment of the recycling process plan



(b) Economical assessment of current recycling practice



(c) Environmental assessment results



(d) Eco2-efficiency of different EOL options

Fig 8. The Assessment module of the CARPP system

7 Concluding Remarks

The large amount of WEEE produced every year, the legislative pressures to divert this waste from the landfills as well as the high residual value of the materials contained in this waste will significantly impact the EOL management of EEE. The authors argue that the current ad hoc approaches to WEEE recycling will not provide the long-term solutions for environmentally friendly and economically justifiable recovery activities in this sector. Furthermore, one of the recent trend in EEE products has been the reduction of the amount of precious metals (gold, palladium, silver, etc) contained in these products to reduce the manufacturing cost. The recovery of these precious metals has been one of the main economic motivations in current EEE recovery and recycling practices. This further highlights the need to improve the environmental and economical performance of WEEE recovery activities to ensure long-term sustainability of EEE

recovery sector. The research reported in this paper has presented a novel computer-aided recycling process planning system to determine the most suitable EOL options for WEEE.

It is proposed that the utilisation of CA*R*PP system within the EEE recovery facilities can increase value recovery, introduce process consistency and improve the development of bespoke recycling process plans which are based on the most updated product information and knowledge related to existing recycling processes. These recycling process plans can then be stored in an operational database and applied to similar product families in the future.

A further use of the CA*R*PP system which currently being investigated is as the operational support on the shop floor within the contemporary semi-automated recovery facilities to provide detailed and dynamic instructions via live computer platform to operators. These facilities are being set up in various EU countries to process a large volume of a wide range of EEE products in response to the requirement for massive increase in recovery capacity to meet the targets set by the WEEE directive. Such facilities are expected to process a wide range of WEEE through a semi-automated de-pollution/disassembly line before hulks are sent for shredding and material separation, and therefore the provision of timely information on the required processes to operators will significantly improve the throughput time and consequently the revenues from these facilities. Finally, the authors are of the opinion that the information and knowledge contained in the CA*R*PP system will provide invaluable support for the design of future electrical and electronic products to improve their EOL recovery performance.

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Appendix 3

Eco-indicator 99 Methodology

Introduction

This appendix provides a brief description of the Eco-indicator 99 methodology which is used to calculate the ecological impacts of WEEE recovery and recycling activities in this thesis. A brief background of the Eco-indicator 99 method is given along with a description of the standard eco-indicators. This is followed by a number of sample tables containing standard eco-indicators values for materials as well as recycling processes and waste treatment.

A3.1 Background
A3.2 Description of the Standard Eco-indicators
A3.3 Sample Standard Eco-indicator Tables

A3.1 Background

Life Cycle Assessment (LCA) is used to calculate the environmental aspects of products throughout the product life cycle. It helps to determine the interaction between a product and the environment. LCA starts with an inventory of all emissions and resource consumption during a product's entire life cycle. The result of this inventory is an inventory table containing a list of emissions, consumed resources etc. Usually inventory table are very long and hard to interpret. Although, it is a common practice to sort the impacts by the impact category, and calculate a score of impact categories such as greenhouse effect, ozone depletion, acidification, eutrophication, etc., how these impact categories are to be weighted is not clear. This is why mostly LCA results are not interpreted clearly.

Eco-indicator 99 is a top-down damage oriented method for life cycle assessment, and is based on the predecessor, the Eco-Indicator 95 (Goedkoop *et al.* 1996), which is summarised in the Figure A3.1. Within a LCA it is possible to determine the contribution of a product life cycle to the different environmental problems but due to the lack of mutual weighting of the environmental effects the total environmental impact remains unknown. Eco-indicator 99 method has resolved this problem by expanding the LCA method to include a weighting method. The method enables one single score, known as Eco-indicator, to be calculated for the total environmental impact based on the calculated environmental effects (Goedkoop and Spriensma 2001). The Eco-indicator is calculated by using the data which have been collected in advance for the most common material and processes.

The standard Eco-indicator of a material or process is thus a number that indicates the environmental impact of that material or process and is a dimensionless figure. In a standard Eco-indicator, environmental effects of a material or process are translated to actual damage inflicted to eco-system quality, human health and resource depletion, and the final result is expressed in a single score (i.e. a point) that indicates the overall damage to the environment. One point (Pt) is representative for one thousandth of the yearly environmental load of one average European inhabitant. Standard Eco-indicator are usually listed in unit milli-point (mPt) (800mPt = 0.8Pt).

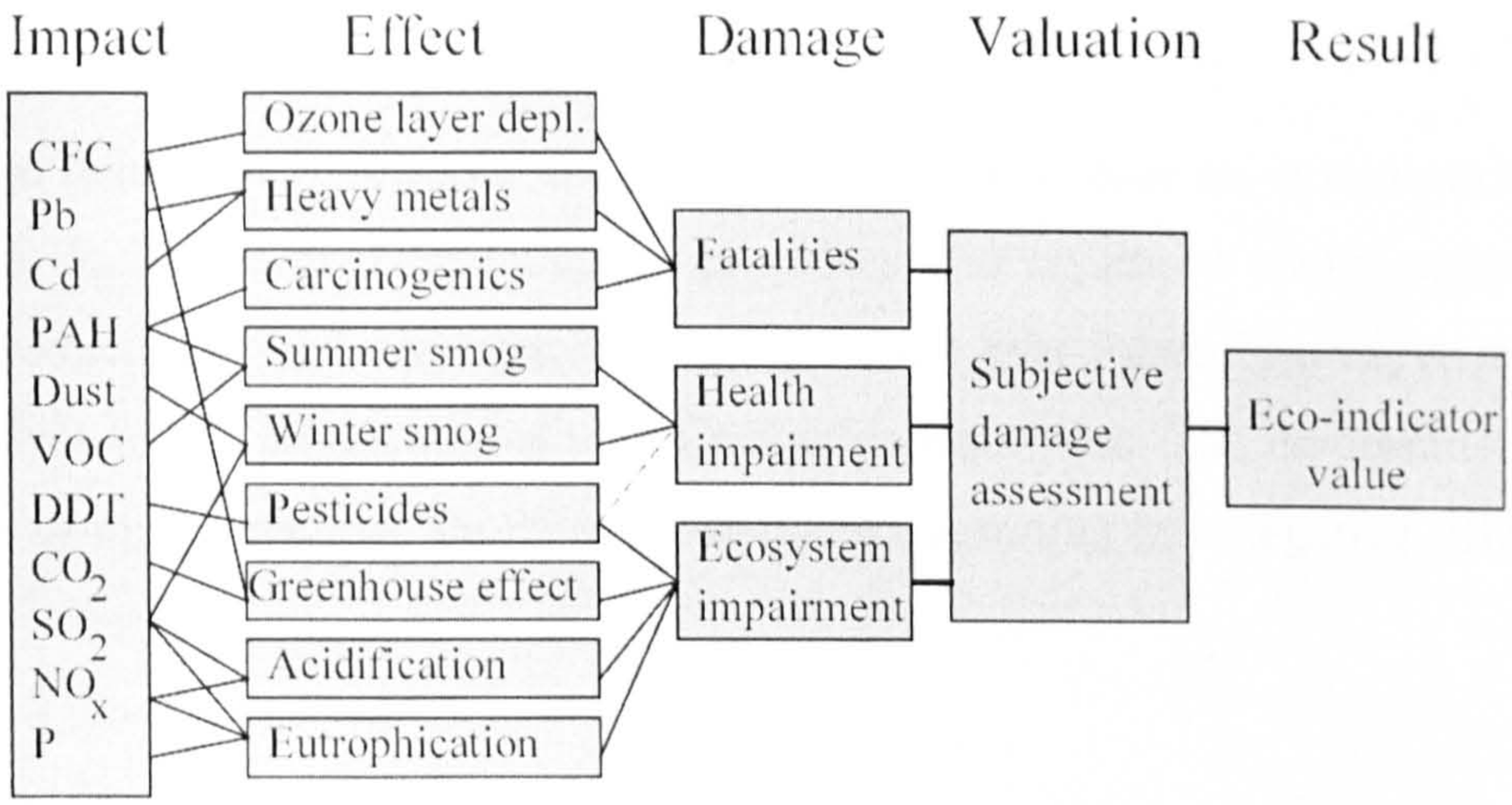

Figure A3.1: Graphical representation of the Eco-indicator 95 methodology (Goedkoop *et al.* 1996)

A3.2 Description of Standard Eco-indicators

Standard Eco-indicator values are available for:-

- ***Production of Materials*** indicating the standard eco-indicator values for producing 1kg of the material. In determining this indicator all the processes are included from the extraction of the raw material up to an including the last production stage, resulting in bulk material.

- ***Production Processes*** indicating the treatment and processing of various materials (e.g. bending, pressing, injection moulding).

- ***Transport Processes*** indicating the impact of emissions caused by the extraction and production of fuel and generation of energy from fuel during transport.

- ***Energy Generation Processes*** indicating the extraction and production of fuels and energy conversion and electricity generation.

- ***Waste Processing and Recycling*** indicating the impacts of different waste processing routes e.g. incineration, disposal to landfill and material recycling.

A3.21 Negative values of Eco-indicators of waste processing

It is to be noted that waste processing and recycling processes cause an environmental load as all other processes do. However these recycling processes also results in useful products e.g. scrap steel. These products can be interpreted as 'environmental gain - usually a negative eco-indicator value', as they avoid the production of virgin materials elsewhere. The environmental effects for the production of virgin material are therefore deducted, resulting into negative values of the eco-indicators.

A3.3 Sample Standard Eco-indicator Tables

Production of ferro metals (in millipoints per kg)

	Indicator	Description
Cast iron	240	Casting iron with > 2% carbon compound
Converter steel	94	Block material containing only primary steel
Electro steel	24	Block material containing only secondary scrap
Steel	86	Block material containing 80% primary iron, 20% scrap
Steel high alloy	910	Block material containing 71% primary iron, 16% Cr, 13% Ni
Steel low alloy	110	Block material containing 93% primary iron, 5% scrap, 1% alloy metals

Production of non ferro metals (in millipoints per kg)

	Indicator	Description
Aluminium 100% Rec.	60	Block containing only secondary material
Aluminium 0% Rec.	780	Block containing only primary material
Chromium	970	Block, containing only primary material
Copper	1400	Block, containing only primary material
Lead	640	Block, containing 50% secondary lead
Nickel enriched	5200	Block, containing only primary material
Palladium enriched	4600000	Block, containing only primary material
Platinum	7000000	Block, containing only primary material
Rhodium enriched	12000000	Block, containing only primary material
Zinc	3200	Block, containing only primary material (plating quality)

Recycling of waste (in millipoints per kg)

	Indicator			Description
	Total	Process	Avoided product	Environmental load of the recycling process and the avoided product differs from case to case. The values are an example for recycling of primary material.
Recycling PE	-240	86	-330	if not mixed with other plastics
Recycling PP	-210	86	-300	if not mixed with other plastics
Recycling PS	-240	86	-330	if not mixed with other plastics
Recycling PVC	-170	86	-250	if not mixed with other plastics
Recycling Paper	-1,2	32	-33	Recycling avoids virgin paper production
Recycling Cardboard	-8,3	41	-50	Recycling avoids virgin cardboard production
Recycling Glass	-15	51	-66	Recycling avoids virgin glass production
Recycling Aluminium	-720	60	-780	Recycling avoids primary aluminium.
Recycling Ferro metals	-70	24	-94	Recycling avoids primary steel production

Waste treatment (in millipoints per kg)

	Indicator	Description
Incineration		Incineration in a waste incineration plant in Europe. Average scenario for energy recovery. 22% of municipal waste in Europe is incinerated
Incineration PE	-19	Indicator can be used for both HDPE and LDPE
Incineration PP	-13	
Incineration PUR	2,8	Indicator can be used for all types of PUR
Incineration PET	-6,3	
Incineration PS	-5,3	Relatively low energy yield, can also be used for ABS, HIPS, GPPS, EPS
Incineration Nylon	1,1	Relatively low energy yield
Incineration PVC	37	Relatively low energy yield
Incineration PVDC	66	Relatively low energy yield
Incineration Paper	-12	High energy yield CO_2 emission disregarded
Incineration Cardboard	-12	High energy yield CO_2 emission disregarded
Incineration Steel	-32	40% magnetic separation for recycling, avoiding crude iron (European average)
Incineration Aluminium	-110	15% magnetic separation for recycling, avoiding primary aluminium
Incineration Glass	5,1	Almost inert material, indicator can be used for other inert materials
Landfill		Controlled landfill site. 78% of municipal waste in Europe is landfilled
Landfill PE	3,9	
Landfill PP	3,5	
Landfill PET	3,1	
Landfill PS	4,1	Indicator can also be used for landfill of ABS
Landfill EPS foam	7,4	PS foam, 40 kg/m^3, large volume
Landfill foam 20kg/m^3	9,7	Landfill of foam like PUR with 20kg/m^3
Landfill foam 100kg/m^3	4,3	Landfill of foam like PUR with 100kg/m^3
Landfill Nylon	3,6	
Landfill PVC	2,8	Excluding leaching of metal stabilizer
Landfill PVDC	2,2	
Landfill Paper	4,3	CO_2 and methane emission disregarded
Landfill Cardboard	4,2	CO_2 and methane emission disregarded
Landfill Glass	1,4	Almost inert material, indicator can also be used for other inert materials
Landfill Steel	1,4	Almost inert material on landfill, indicator can be used for ferro metals
Landfill Aluminium	1,4	Almost inert material on landfill, indicator is valid for primary and recycled alu.
Landfill of 1 m^3 volume	140	Landfill of volume per m^3, use for voluminous waste, like foam and products
Municipal waste		In Europe, 22% of municipal waste is incinerated, 78% is landfilled. Indicator is not valid for voluminous waste and secondary materials
Municipal waste PE	-1,1	
Municipal waste PP	-0,13	
Municipal waste PET	1	
Municipal waste PS	2	Not valid for foam products
Municipal waste Nylon	3,1	
Municipal waste PVC	10	
Municipal waste PVDC	16	
Municipal waste Paper	0,71	
Municipal waste Cardboard	0,64	
Municipal waste ECCS steel	-5,9	Valid for primary steel only!
Municipal waste Aluminium	-23	Valid for primary aluminium only!
Municipal waste Glass	2,2	

Table A3.1: Standard Eco-indicator values for Materials, Waste Processing and Recycling

Appendix 4

Computer Aided Recycling Process Planning for End-of-Life Electrical and Electronic Equipment

Introduction

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Computer-aided recycling process planning for end-of-life electrical and electronic equipment

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Abstract: The significant environmental cost associated with management of products at the end-of-life has resulted in the emergence of 'producer responsibility' legislations to encourage increase in recovery and recycling practices. In the case of electrical and electronic equipment, one such legislation, namely the 'Waste from Electrical and Electronic Equipment Directive', requires manufacturers to assume financial and legal liability for recovery and recycling of their products at the end-of-life. The current recycling applications of electrical and electronic waste are often developed on *ad hoc* basis and mainly attributable to the hidden economic value within used products. However, owing to stricter regulations on end-of-life product recycling, it is now essential to evaluate the recycling costs and environmental benefits of reclaimed products and materials as well as the selection of appropriate recycling strategy. The present paper describes the initial investigation in the realization of a computer-aided recycling process planner for electrical and electronic products. The assertion made is that such a systematic approach to producing bespoke eco-efficient recycling process plans for individual products will significantly improve the value recovery from recycling activities.

Keywords: recycling process planning, WEEE, end-of-life

1 INTRODUCTION

The production of electrical and electronic equipment (EEE) is increasing owing to technological innovation, market expansion, shorter product life cycles, and improvements in economy [1]. This development is leading to a huge increase in waste from electrical and electronic equipment (WEEE). It had been predicted that 7.3 million tonnes of WEEE were created in Europe in 2002, with an estimated annual growth rate of 3–5 per cent [2]. Although a part of this waste (mainly white goods) has been recycled, a large proportion of WEEE that contains potentially recyclable materials ends up in landfills. The consumption of scarce materials in the manufacture of EEE and its disposal to scarce landfill sites along with environmental problems caused by electrical and electronic (E&E) waste has resulted in the introduction of a European producer responsibility directive for such waste, namely the WEEE directive.

At present, a limited volume of WEEE is collected and sent for processing to authorized recovery facilities. The recovery treatment of this waste currently is mainly based on the capabilities and available resources within these facilities, without any detailed considerations of environmental benefits of such recycling activities. Furthermore, these recycling activities are solely focused on the reclamation of most valuable components and materials, with a substantial amount of waste still being sent to landfill in the form of shredder residue. This highlights the need to improve the value recovery from such recycling activities to ensure a larger proportion of components and materials being recovered from WEEE. Hence, the decision on the selection of the most appropriate recycling processes needs to be based on the consideration of both the environmental and economical factors involved in WEEE recycling.

The research reported in the present paper aims to take advantage of the benefits provided by a systematic approach to process planning experienced in

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manufacturing applications [3] and to apply a similar principle to increase the efficiency of recycling activities. This paper presents initial considerations on the development of a computer-aided recycling process planner (CARPP) for electrical and electronic products based on environmental and economical assessment of different recycling scenarios. A brief review of the most relevant research together with an end-of-life (EOL) model for WEEE based on current recycling practices are provided in the initial sections of the current paper. The main sections describe a framework for recycling process planning together with the design and specification of a CARPP system.

2 BRIEF REVIEW OF THE MOST RELEVANT RESEARCH

The two important aspects considered in EOL research are recycling cost and environmental impact. These aspects should form the basis for any recycling strategy selection. Existing research, however, usually focuses on the economic aspects of EOL recycling. Most of the studies for recycling cost estimation have adopted a bottom-up approach where the estimation is conducted based on operation breakdown and summation of detailed cost items. For material recovery, several studies estimate recycling cost including disassembly cost, shredding and separation cost, disposition cost, and revenue from reclaimed materials. Reimer *et al.* [4] have proposed a recycling model to minimize the cost of different EOL activities such as collection, disassembly, and material separation sequences by establishing separate models for each activity and using genetic algorithms. Other examples include Tsao [5] and Stutz [6]. Much attention is paid to disassembly as it plays an important role in the whole recycling economics. Tang *et al.* [7] and Gerner *et al.* [8] systematically investigated the disassembly sequence and related operations so that disassembly cost can be optimized.

On the other hand, there is also an ongoing research to evaluate the environmental performance of different recycling scenarios. There is the life cycle assessment (LCA), which is commonly used to determine the environmental impacts of a product throughout its lifetime. Some studies have incorporated both cost estimation and environmental impact estimation. For example, Lee *et al.* [9] tried to find an alternative that can both maximize profit and minimize environmental impact; they use a coffee maker as an example. Zhang *et al.* [10] adopted the analytical hierarchic process (AHP) to find the best recycling strategy. The AHP-based evaluation considered environmental impact, cost, and reclaimed materials as the major criteria for strategy determination. Huisman *et al.* [11] described 'the quotes for the environmentally weighted recyclability' (QWERTY) approach, which focuses on the determination of environmentally weighted recycling scores. The concept describes the environmental performance of recycling of waste products. To reduce the environmental impact of EOL EEE and increase the economic benefits at the same time, the CARPP described in the current paper integrates the environmental and economic concerns to apply a holistic assessment to facilitate E&E waste recycling.

3 AN END-OF-LIFE MODEL FOR WEEE

EEE is typically divided into large household appliances, information technology (IT) equipment, consumer equipment, and small electrical appliances. Currently, large appliances are mainly collected together with scrap metals at the municipal collection centres. After dismantling and removal of polychlorinated biphenyl (PCB) capacitors, and mercury-containing components (switches), this fraction is added to scrap metals and mechanically separated in coarse shredding facilities. IT equipment and appliances with cathode ray tube (CRT) are gathered separately and dismantled. Casings (plastic and partly wood) are separated and presently still landfilled. Hazardous components such as large capacitors and buffer batteries and accumulators as well as liquid crystal displays (LCDs) are removed and specially treated as hazardous waste. Small electrical appliances are at first submitted to the removal of hazardous components (for instance switches and relays containing mercury, PCB capacitors, batteries, etc.) and these parts are forwarded to specific treatment options according to the special type of pollutant. The appliances of which the hazardous fractions are removed are mechanically processed. By this treatment procedure mainly the metal-containing fraction is recovered. The remaining fraction, containing mainly plastic, is thermally treated or landfilled. According to the Association of Plastics Manufactures in Europe (APME), WEEE contains approximately 38 per cent ferrous metals, 28 per cent non-ferrous metals, 19 per cent plastics, and 4 per cent glass. As WEEE is a mixture of various materials, it can be regarded as a resource of metals, such as copper, aluminium, gold, and plastics. The complexity of materials contained within each product and the huge variety of products in EEE make *ad hoc* applications of WEEE recycling highly ineffective in terms of both ecology and economy. The review of these EOL activities within different recovery and recycling facilities has highlighted that there is little consistency regarding WEEE recycling owing to lack of formal procedures to determine the best course of action for individual products. A model encompassing different

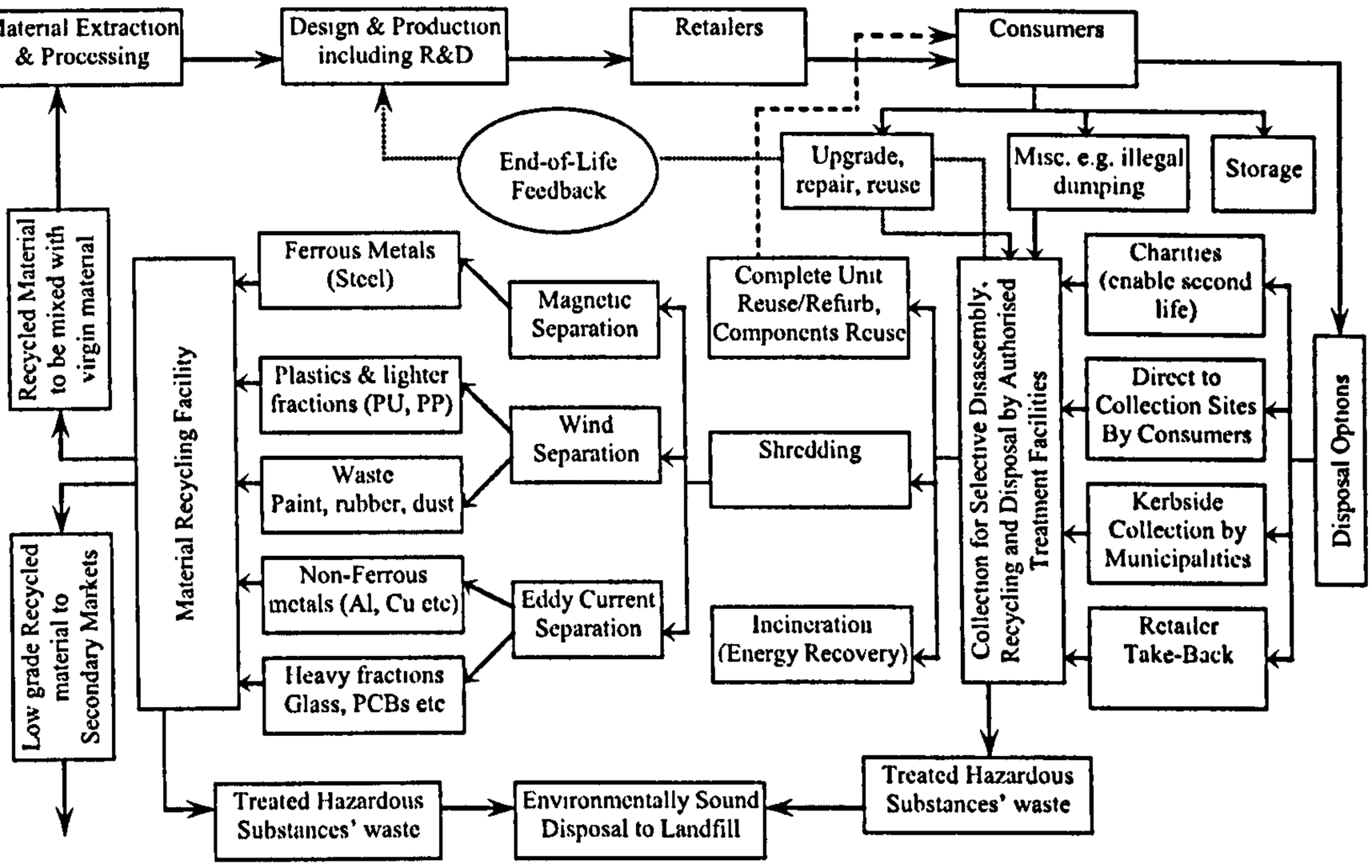

Fig. 1 EOL management model for EEE

activities in EOL management of WEEE is presented in Fig. 1.

The existing and future concerns on disposal and recycling of WEEE highlight the need for a systematic management tool effectively to maximize the recyclability of EOL products and minimize the environmental impact of recycling and disposal. The following sections describe a systematic approach for CA*R*PP, which is set to improve the current state of E&E recycling.

4 AN INTEGRATED FRAMEWORK FOR EEE RECYCLING

The general environmental concerns with respect to discarded EEE are related to conservation of resources, potential toxicity after discarding, and the reduction of landfill and incineration volumes. Traditionally, take-back initiatives were developed for products with a positive EOL value such as copiers, medical equipment, or computer mainframes. However, at present, a large proportion of consumer electronic products have a negative EOL value, which means that take-back initiatives for these products will only be developed when driven by legislation. Clearly, the major challenge for the next generation of recovery facilities will be to minimize the overall costs for EOL treatment of discarded products (i.e. economically justifiable) and to maximize the environmental benefits of such activities (i.e. ecologically friendly). Therefore, any comprehensive framework for recycling process planning should include the concurrent considerations of relevant environmental and economic parameters as well as the legislative requirements. Figure 2 depicts one such framework, referred to as the Eco^2 (ecological and economical) framework, for the generation of recycling process plans. A further complexity related to the recycling process planning is the required product data, which typically can be obtained from the product design. However, currently in most cases access to

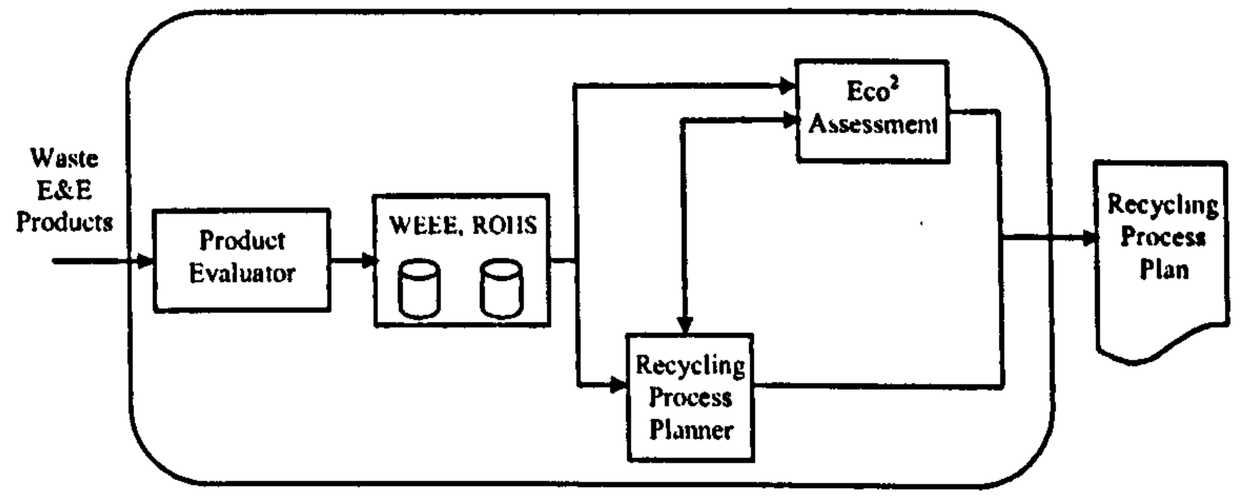

Fig. 2 Major tasks in Eco^2 framework

initial product design data is not available or access to it is restricted. Therefore, a product evaluation stage has been included as part of the framework to generate the data required for recycling process planning.

5 COMPUTER-AIDED RECYCLING PROCESS PLANNER

Process planning in manufacturing applications is an established field that comprises the selection and sequencing of processes and operations to transform a chosen raw material into a finished component in discrete part manufacture. Computer-aided process planning (CAPP) has nowadays become common place in most applications and is preferred over the traditional manual process planning to introduce consistency in planning. There are two basic approaches to CAPP: the generative and variant approaches [3]. The generative approach is based on developing a completely new process plan for every part. It uses the decision logic, formulae, algorithms, and geometric analysis and is considered to be the best approach for manufacturing process planning. On the other hand, the variant approach is similar to the manual process planning as it retrieves an existing standard plan and modifies it to suit the given product. This standard plan is usually for a complex product that incorporates all the features for a particular group or family of products. The process plan for the product under consideration can be compiled by retrieving those processes in the standard plan that are relevant and grouping them to generate a customized process plan for the product.

In the case of recycling process planning, the nature and range of processes is not as complicated as in manufacturing and there is a huge potential of the reuse of the recycling process plans owing to the products, parts, and components commonality. The present authors argue that the adaptability and flexibility of the variant process planning makes such an approach particularly suitable for the recycling process planning. Therefore, based on the product categories used in the WEEE directive, a variant-based approach to recycling process planning is developed. In this approach, the generation of the process plan starts with evaluation of the product under consideration to identify the valuable parts and hazardous substances that need to be dismantled and removed in the initial stages. Then, depending on the remaining material mix in the hulk, a number of shredding and separation processes are considered and assigned before the final stage, namely the operations required for safe disposal of remaining material (commonly referred to as shredder residue). Based on this variant approach, and using the Microsoft Excel, a CA*R*PP has been implemented that incorporates a simple and yet effective generic methodology for the multi-objective decision-making problem of material recycling and disposition of E&E products (see Fig. 3(a)). The CA*R*PP starts by gathering the material breakdown of given product and passes this information to the recycling process planner module. It also identifies any hazardous material requiring selective treatment to assign feasible and appropriate recycling processes. The CA*R*PP contains the database of recycling processes that have been identified through the survey of existing applications, and are grouped together in this database. Information obtained from the product evaluator module controls the recycling processes that are included in the recycling process plan, as each product attribute is linked to one or more sub-operations in the process plan generated for an individual product. The CA*R*PP system also calculates and analyses the environmental impact and cost of the recycling processes as part of the Eco^2 assessment module. A typical recycling process plan for a refrigerator generated by the CA*R*PP is illustrated in Fig. 3(b).

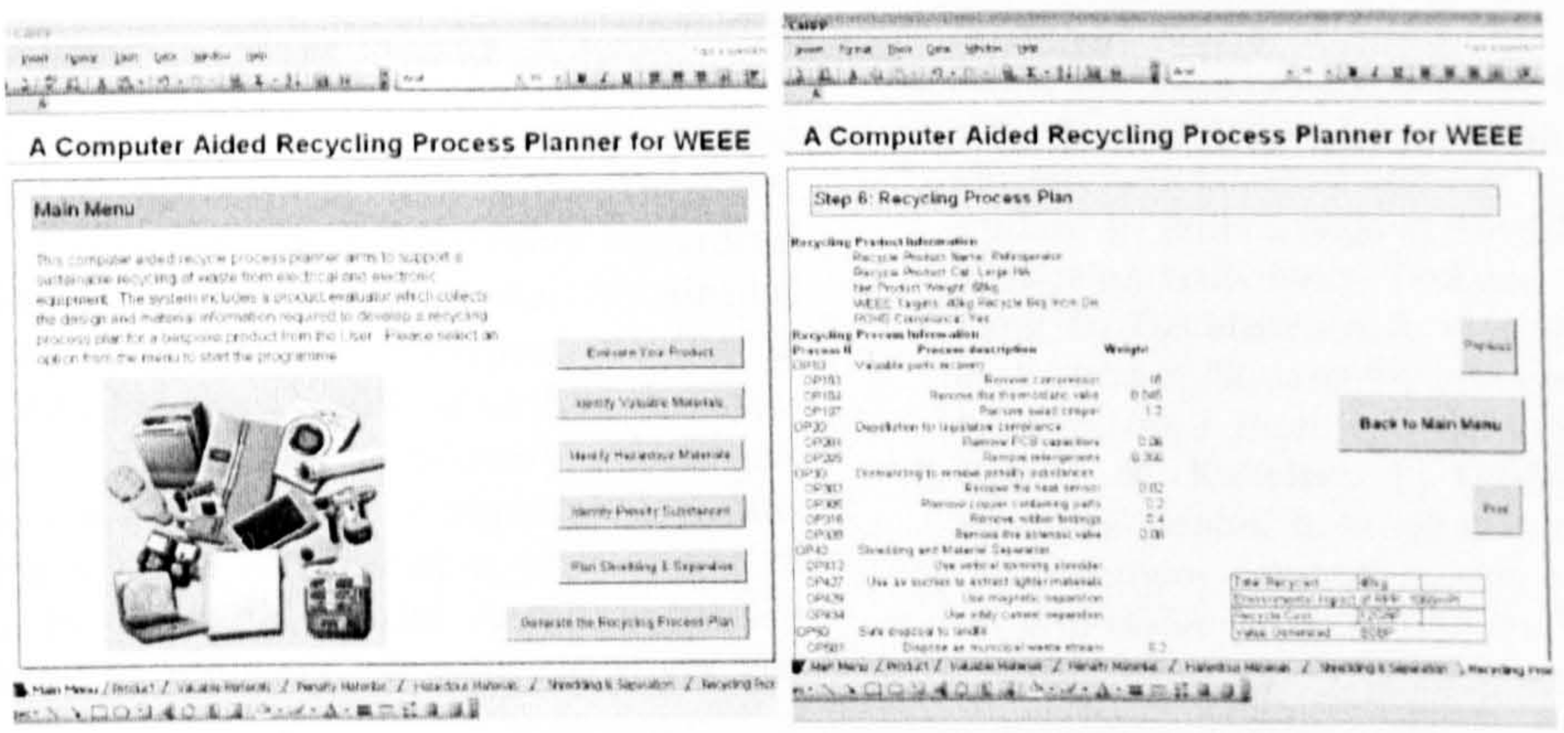

Fig. 3 Screenshots of CA*R*PP: (a) main menu of CA*R*PP; (b) a typical recycling process plan

Typically the quality of variant-based CAPP is very much dependent on the gradual improvement of the 'generic process plan' used as the core of planning activities and the heuristics (or algorithm) used to select a subset of operations and sub-operations for a product under consideration. This can only be achieved through a large number of case studies, which extend and improve the information and knowledge stored in such CAPP. Hence, a comprehensive programme of case studies is planned based on different categories of products in the WEEE such as large household appliances, consumer equipment, small household appliances, IT equipment, etc. to improve the decision-making process at the heart of the CA*R*PP.

6 CONCLUDING DISCUSSIONS

Increased environmental awareness of society and upcoming legislation are challenging the electrical and electronics industry to reduce the environmental impacts of WEEE and associated end-of-life costs. Despite the technological advances in electronics manufacturing, product recovery and recycling still remain cost/time bottlenecks in this sector and industry needs to come up with environmentally friendly and economically justifiable recycling plans for their products to remain competitive. The present paper has described a CA*R*PP to improve the EOL recovery of EEE. It is argued that the adoption of such a systematical approach to the generation of bespoke recycling process plans for various products will significantly improve the environmental performance and will also maximize the 'value recovery' from recycling processes.

Currently, any used product that is received for the first time by a recovery facility is examined in an assessment workshop, before determining the recovery processes required to be used for the product. It is envisaged that the CA*R*PP can be used within such assessment workshops to speed up, introduce consistency, and improve the development of bespoke recycling process plans that are based on the most up-to-date information and knowledge related to existing recycling processes. These recycling process plans can then be stored in an operational database and applied to similar product families in the future. A further use that is to be investigated for the CA*R*PP is within the contemporary semi-automated recovery facilities. These facilities are being set up in various EU countries to process a large volume of a wide range of E&E products in response to the requirement for massive increase in recovery capacity to meet the target set by the WEEE directive. In such facilities, a product is pulled into a workstation from the conveyor belt feeding the line, is de-polluted, and selected disassembly is performed before the hulk is sent for shredding and separation processes further down the recovery line. In such applications, it is envisaged that the recycling process plans for various products generated and stored within CA*R*PP can be fed directly to the recovery line via live computer platforms and used by the operators to identify the de-pollution and disassembly requirements to be undertaken on the product. Finally, the current authors argue that the information and knowledge contained in such CA*R*PP will provide invaluable support for the design of future E&E products to improve their EOL recovery.

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Appendix 5

Case Studies' Product Evaluation and Assessment Results

Introduction

This appendix contains the full implementation of the RPP framework through associated CA*R*PP for recycling of the Desktop Computer and the Electric kettle. The first section highlights the product evaluation process conducted for these case studies to generate their bespoke recycling process plans. This is followed by the ecological and economical assessment of these case studies, which is used to evaluate the overall performance of their proposed bespoke recycling process plans.

A5.1 Desktop Computer

A5.2 Electric Kettle

A5.1.1 Product Evaluation for Desktop Computer

Product Evaluation Process...

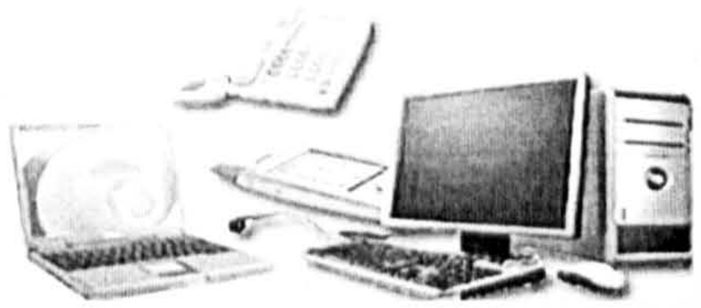
Step 01: Identify your Product:

This module generates the Recycling Process Plans for ten categories of products included in the WEEE Directive. Please use the drop down menus below to select your product

Product Catagory: IT and Telecommunication equipment

Product Type: Personal Computer

Available Products:



WEEE Targets to be met (% age by weight)

	Recovery	Recycling and Reuse
Large household appliances	80%	75%
Small household appliances	70%	50%
IT and Telecommunication Eq	**75%**	**65%**
Consumer equipment	75%	65%
Lighting equipment	70%	50%
Electrical and Electronic tools	70%	50%
Toys, Leisure and Sports Eq	70%	50%
Medical devices	No Target	No Target
Monitoring and Control Equipment	70%	50%
Automatic Dispensers	80%	75%

Weight of selected product (Kg): 37.75

Exit | Main Menu | Step 2 >>

Figure A5.1: Identification of the case study product and its WEEE category

Product Evaluation Process...

Step 02: Identify the Hazardous Materials and Components in your Product

< Personal Computer >

Please tick the boxes representing the hazardous materials and components which are present in your product. Check the indicative weights given and edit them if required.

Hazardous Materials	Weight (kg)
Casing	
Insulation	
☑ CRT	21
Printed wiring boards	
Thermostats	
BFR-Containing plastic	
☑ Batteries	0.03
CFC, HCFC, HCF, HC	
☑ External electric cable	0.2
Refractory ceramic fibres	
Radio active substances	

Hazardous Materials	Weight (kg)
☑ Other Materials	
Mother Board	0.6
Enter the name	0

Important Notes:

Higlighted are the most likely hazardous materials and components which you may find in your product Safe removal and treatment of these materials and components is required by the WEEE Directive.

Total Hazardous Material Weight (kg) 21.83

Exit | Main Menu | << Step 1 | Step 3 >>

Figure A5.2: Hazardous materials in the computer

Product Evaluation Process...

Step 03: Identify the Valuable Materials and Components in your Product

< Personal Computer >

Please tick the boxes representing the valuable materials and components which are present in your product. Check the indicative weights given and edit them if required.

Valuable Materials	Weight (kg)	Valuable Materials	Weight (kg)
[redacted]		☑ Other Materials	
☐ ICs		CD Drive	0.98
☑ Processor	0.21	Enter the name	0
☐ Modem			
☑ Network Card	0.06		
☑ Memory	0.04		
[redacted]			
[redacted]			
☑ Power Supply	1.5		
[redacted]			
[redacted]			
☑ Hard Disk Drive	0.5		

Total Valuable Material Weight (kg) 3.29

Important Notes:

Highlighted are the most likely valuable materials and components which you may find in your product. These valuable materials and components have a high potential for revenue generation . Safe removal and reuse of these valuable materials and components resutls in positive revenue which helps to make recycling of WEEE economically self-sufficient.

Exit | Main Menu | << Step 2 | Step 4 >>

Figure A5.3: Valuable materials in the computer

Product Evaluation Process...

Step 04: Identify the Penalty Materials and Components in your Product

< Personal Computer >

Please tick the boxes representing the penalty materials and components which are present in your product. Check the indicative weights given and edit them if required.

Penalty Materials	Weight (kg)	Penalty Materials	Weight (kg)
[redacted]		☐ Other Materials	
[redacted]		Enter the Name	0
[redacted]		Enter the Name	0
☐ PVC			
☐ Copper			
☑ Cables	0.25		

Total Penalty Material Weight (kg) 0.25

Important Notes:

Highlighted are the most likely penalty materials and componenets which you may find in your product . These penalty materials and components causes serious problems for post-fragmentation material separation. Removing these penalty materials and components before the product hulk is sent to the shredder is a value-added activity which eliminates the contaminations in shredded material streams.

Exit | Main Menu | << Step 3 | Step 5 >>

Figure A5.4: Penalty materials in the computer

Product Evaluation Process ...

Step 05: Shredding and Material Separation for your Product

< Personal Computer >

>> Weight of product before shredding (Kg): 12.38

Based on the generic material composition of WEEE the weight of each material type included in your product is calculated below. Check the weights below and edit them if required.

Each material stream is linked to an appropriate material separation process. Separability efficiency of each material separation process is considered before calculating the total material recovered from the product.

Material Type	Composition (weight %)	Weight (kg)	Process Type	Separatability Efficiency	Material Processed	Material Recovered
☑ Iron and steel	78.2	9.681	Managatic Separation	0.98	9.681	9.487
☑ Flame retarded plastics	2.2	0.272	Skin Floatation	0.70	0.272	0.190
☑ Non-Flame retarded plastics	11.7	1.448	Electrostatic Separation	0.65	1.448	0.941
☑ Wood and plywood	0	0	Air Separation	0.85	0	0
☑ Aluminium	3.6	0.445				
☑ Copper	1.1	0.136	Eddy Current Separation	0.9	0.741	0.666
☑ Other Metals	1.3	0.160				
☑ Glass	0	0				
☑ Rubber	0.2	0.024	Heavy Medium Separation	0.75	0.234	0.175
☑ Concret and ceramics	0	0				
☑ Others	1.7	0.210				

Recalculate — **Total Material Recovered:** 11.45

Exit | Main Menu | << Step 4 | Step 6 >>

Figure A5.5: Composition and post fragmentation separation of the computer

Product Evaluation Process ...

Step 06: Identify Safe Disposal for your Product

< Personal Computer >

Inefficiencies of the material separation processes and economics of available recycling technologies necessitate safe disposal of the shredder residue. Certain hazardous substances removed from WEEE also require safe disposal.

Weight of the Product to be disposed (kg) 1.53

Disposal suitable for landfill	Weight (kg)
☑ Controlled landfill of Skin floatation process waste	0.059
☑ Dispose the waste as MWS	0.111

Disposal suitable for Incineration	
☑ Controlled Incineration of Electrostatic seperation waste	0.376
☑ Incinerate Air separation process fluff	0
☑ Incinerate Heavy medium separation process fluff	0.037
☑ Controlled incincration of other hazardous materials	0.6

Important Notes:

Incineration of WEEE can result in high concentration of metals, heavy metals in the slag, the flue gas or the filter cakes. Care is to be taken to dispose certain materials included in the WEEE which are not suitable for incineration in view of the hazardous nature of the flue gas residues and are better to be sent to controlled landfill.

Exit | Main Menu | << Step 5 | Generate Recycling Process Plan

Figure A5.6: Safe disposal of the computer hulk

Recycling Process Plan...

Step 07: Recycling Process Plan for your Product

The Recycling process plan for: < Personal Computer >

Recycle Product Name: Personal Computer
Recycle Product Category: IT and Telecommunication equipment
Net Product Weight: 37.75
Total Hazardous Material Weight(kg): 21.83
Weight Sent to Shredder(kg): 12.38
Weight disposed as MWS(kg): 0.376

OP100 Depollution for legistlative compliance:

Process ID	Process Description	Weight Processed
Sub-Op103	Remove CRT for Material Recovery	21
Sub-Op107	Remove Batteries for further treatment	0.03
Sub-Op109	Remove External electric cable for Material Recovery	0.2
Sub-Op113	Remove Mother Board for Material Recovery	0.6

OP200 Valuable parts recovery:

Process ID	Process Description	Weight Processed
Sub-Op203	Remove Processor for possible Reuse	0.21
Sub-Op205	Remove Network Card for further treatment	0.06
Sub-Op206	Remove Memory for possible Reuse	0.04
Sub-Op209	Remove Power Supply for Material Recovery	1.5
Sub-Op212	Remove Hard Disk Drive for possible Reuse	0.5
Sub-Op213	Remove CD Drive for possible Reuse	0.98

Weight of the Product Recycled 27.34

Weight of the Product Recovered 28.353

OP300 Dismantling to remove Penalty substances:

Process ID	Process Description	Weight Processed
Sub-Op306	Remove Cables for Material Recovery	0.25

OP400 Shredding and Mechanical Separation:

Process ID	Process Description	Weight Processed
Sub-Op402	Use Air Separation to recover lighter fractions	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	9.487
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.666
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.175
Sub-Op409	Use Skin Floatation to recover FR plastics	0.190
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.941

OP500 Safe Disposal:

Process ID	Process Description	Weight Processed
Sub-Op501	Incinerate Air separation process fluff	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.037
Sub-Op503	Controlled incincration of other hazardous materials	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.059
Sub-Op508	Dispose the waste as MWS	0.111
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.376

Compliance Monitor

Personal Computer	Recovery (%)	Recycling (%)
Targets	75	65
Achieved	**75.11**	**72.42**
Compliance	Yes	Yes

Exit | Save Recycling Process Plan | Environmental Assessment of Recycling Process Plan >>

Figure A5.7: Bespoke recycling process plan for the computer

A5.1.2 Ecological and Economical Assessment of Desktop Computer

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Personal Computer >

Upper and Lower Limits of Environmental Performance for < Personal Computer >

Recycle Product Name: < Personal Computer > Net Product Weight: 37.75

An upper and lower limit of end-of-life Environmental Performance is calculated to evaluate the environmental performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg)		mi x Eli bcs (mPt)	mi x Eli wcs (mPt)
		Material Substitution (Eli bcs)	Landfill (Eli wcs)		
Steel	13.63	-86	1.4	-1172.18	19.08
FR Plastics	3.4	-383.3	3.95	-1303.22	13.43
NFR Plastics	5.83	-383.3	3.95	-2234.64	23.03
Wood / Plywood	0	-39	4.2	0	0
Aluminium	0.53	-780	1.4	-413.4	0.74
Copper	2.11	-1400	1.4	-2954	2.95
Other metals	0.37	-1150.9	1.4	-425.83	0.52
Glass	10.19	-66	1.4	-672.54	14.27
Rubber	0.03	-360	7.4	-10.8	0.22
Concrete	0	-3.8	1.4	0	0
Others	1.62	-100	1.4	-162	2.27

Upper limit of Ecological Performance = -9348.61

Lower limit of Ecological Performance = 301.24

Upper limit of environmental performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any environmental burden of treatment processes."

Lower limit of environmental performance is calaculated considering that every material in the Product is ending up in the landfill without any environmental burden of treatment processes."

Exit | Recycling Process Plan | Step 2 >>

Figure A5.8: Calculation of the ecological performance limits

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Personal Computer >

Upper and Lower Limits of Economical Performance for < Personal Computer >

Recycle Product Name: < Personal Computer > Net Product Weight: 37.75

An upper and lower limit of end-of-life Economical Performance is calculated to evaluate the economical performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg)		mi x Cli bcs (£)	mi x Cli wcs (£)
		Material Revenue (Cli bcs)	Disposal Cost (Cli wcs)		
Steel	13.63	0.07	0.03	0.95	0.41
FR Plastics	3.4	0.1	0.03	0.34	0.1
NFR Plastics	5.83	0.1	0.05	0.58	0.29
Wood / Plywood	0	0	0.03	0	0
Aluminium	0.53	0.8	0.03	0.42	0.02
Copper	2.11	2.8	0.03	5.91	0.06
Other metals	0.37	4.8	0.03	1.78	0.01
Glass	10.19	0.03	0.04	0.31	0.41
Rubber	0.03	0.1	0.03	0	0
Concrete	0	0	0.03	0	0
Others	1.62	0	0.08	0	0.13

Upper limit of Economical Performance = -10.29

Lower limit of Economical Performance = 13.43

Cost of Depollution = 12

Upper limit of economical performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any economical burden of treatment processes."

Lower limit of economical performance is calaculated considering that every material in the Product is ending up in the landfill."

Exit | Recycling Process Plan | Step 2 >>

Figure A5.9: Calculation of the economical performance limits

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Personal Computer >

Environmental Impact Assessment of the current recycling practice for < Personal Computer >

Recycle Product Name: < Personal Computer > **Hazardous Materials Weight:** 21.83 **Shredding Weight:** 28.52

End-of-life environmental performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) (Eli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
		Material Substitution	Landfill	Incineration			
Steel	10.3	-86	-	-	0.95	0.8	-673.21
FR Plastics	2.57	-	3.95	-	1	1	10.15
NFR Plastics	4.41	-383.3	-	-	0.70	0.6	-709.95
Wood / Plywood	0	-	-	-12	1	1	0
Aluminium	0.4	-780	-	-	0.85	0.65	-172.38
Copper	1.6	-1400	-	-	0.85	0.7	-1332.8
Other metals	0.28	-	-	-32	1	1	-8.96
Glass	7.7	-	1.4	-	1	1	10.78
Rubber	0.02	-	7.4	-	1	1	0.15
Concrete	0	-	1.4	-	1	1	0
Others	1.23	-	1.4	-	1	1	1.72

Actual Ecological Performance = -2704.22

Exit | Recycling Process Plan | Step 3 >>

Figure A5.10: Calculation of actual ecological performance through shredding

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Personal Computer >

Economical Impact Assessment of the current recycling practice for < Personal Computer >

Recycle Product Name: < Personal Computer > **Hazardous Materials Weight:** 21.83 **Shredding Weight:** 28.52

End-of-life economical performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Cli ap x PEi x Gi (£)
		Processing Cost	Disposal Cost	Material Revenue			
Steel	10.3	0.02	-	0.07	0.95	0.8	-0.39
FR Plastics	2.57	0.025	0.015	-	1	1	0.1
NFR Plastics	4.41	0.025	-	0.1	0.70	0.6	-0.14
Wood / Plywood	0	0.018	0.015	-	1	1	0
Aluminium	0.4	0.028	-	0.8	0.85	0.65	-0.17
Copper	1.6	0.030	-	2.8	0.85	0.7	-2.64
Other metals	0.28	0.030	0.015	-	1	1	0.01
Glass	7.7	0.024	0.04	-	1	1	0.49
Rubber	0.02	0.024	0.015	-	1	1	0
Concrete	0	0.015	0.015	-	1	1	0
Others	1.23	0.015	0.08	-	1	1	0.12

Actual Economical Performance = -2.62

Cost of Depollution = 12

Exit | Recycling Process Plan | Step 3 >>

Figure A5.11: Calculation of actual economical performance through shredding

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Personal Computer >

Environmental Impact Assessment of the Proposed Recycling Process Plan for < Personal Computer >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Environmental Impact (mPt/kg) (Eli ap)				Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
			Material Substitution	Landfill	Incineration	Actual		
Sub-Op103	Remove CRT for Material Recovery	21	-83.5	1.935	-7.28	-83.5	0.6	-1052.1
Sub-Op107	Remove Batteries for further treatment	0.03	-150	-	-5.5	-5.5	1	-0.16
Sub-Op109	Remove External electric cable for Material Recovery	0.2	-891.6	2.67	-82.7	-891.6	0.75	-133.74
Sub-Op113	Remove Mother Board for Material Recovery	0.6	-649.8	9.8	-25.4	-649.8	0.7	-272.92

Valuable Recovery

Sub-Op203	Remove Processor for possible Reuse	0.21	-514.4	1.4	-	-514.4	0.7	-75.62
Sub-Op205	Remove Network Card for further treatment	0.06	-509	3.16	-	-509	0.75	-22.9
Sub-Op206	Remove Memory for possible Reuse	0.04	-566.2	2.24	-	-566.2	0.75	-16.99
Sub-Op209	Remove Power Supply for Material Recovery	1.5	-698.3	2.1	-	-698.3	0.75	-785.59
Sub-Op212	Remove Hard Disk Drive for possible Reuse	0.5	-147.6	1.4	-	-147.6	0.75	-55.35
Sub-Op213	Remove CD Drive for possible Reuse	0.98	-230.5	1.95	-	-230.5	0.75	-169.42

Penalty Removal

Sub-Op306	Remove Cables for Material Recovery	0.25	-891.6	2.67	-	-891.6	0.75	-167.18

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-39	4.2	-12	-12	0.75	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	9.487	-86	1.4	-32	-86	0.8	-652.71
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.666	-1115.1	1.4	-110	-1115.1	0.65	-482.73
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.175	-150	3.1	3.95	-150	0.6	-15.75
Sub-Op409	Use Skin Floatation to recover FR plastics	0.190	-383.4	3.95	37	3.85	0.6	0.44
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.941	-383.4	3.95	-13	-383.3	0.6	-216.41

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	4.2	-12	-12	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.037	-	3.1	3.95	3.95	1	0.15
Sub-Op503	Controlled incincration of other hazardous materials	0	-	7.83	-20.8	-20.8	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.059	-	3.95	37	3.95	1	0.23
Sub-Op508	Dispose the waste as MWS	0.111	-	1.4	-15	-15	1	-1.66
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.376	-	3.95	-13	-13	1	-4.89

Actual Ecological Performance = -4525.29

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure A5.12: Calculation of actual ecological performance of recycling through recycling process plan

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Personal Computer >

Economical Impact Assessment of the Proposed Recycling Process Plan for < Personal Computer >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)				Grade (Gi)	mi x Cli ap x PEi x Gi (£)
			Disassembly Cost	Processing Cost	Disposal Cost	Material Revenue		
Sub-Op103	Remove CRT for Material Recovery	21	8	0.015	-	0.2864	0.7	4.01
Sub-Op107	Remove Batteries for further treatment	0.03	2	0.015	0.025	-	1	2
Sub-Op109	Remove External electric cable for Material Recovery	0.2	0.4	0.015	-	1.1	0.75	0.24
Sub-Op113	Remove Mother Board for Material Recovery	0.6	3	0.025	-	0.9	0.85	2.55

Valuable Recovery

Sub-Op203	Remove Processor for possible Reuse	0.21	0.5	0.015	-	0.86	0.7	0.38
Sub-Op205	Remove Network Card for further treatment	0.06	0.2	0.015	-	0.52	0.75	0.18
Sub-Op206	Remove Memory for possible Reuse	0.04	0.2	0.015	-	0.9	0.75	0.17
Sub-Op209	Remove Power Supply for Material Recovery	1.5	0.2	0.015	-	0.85	0.75	-0.74
Sub-Op212	Remove Hard Disk Drive for possible Reuse	0.5	0.25	0.015	-	0.95	0.75	
Sub-Op213	Remove CD Drive for possible Reuse	0.98	0.15	0.015	-	0.54	0.75	-0.24

Penalty Removal

Sub-Op306	Remove Cables for Material Recovery	0.25	0.1	0.015	-	1.1	0.75	-0.1

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-	0.018	0.015	0	1	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	9.487	-	0.02	0	0.07	0.8	-0.38
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.666	-	0.03	0	1.88	0.65	-0.8
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.175	-	0.025	0.015	0	1	0.01
Sub-Op409	Use Skin Floatation to recover FR plastics	0.190	-	0.025	0.015	0	1	0.01
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.941	-	0.025	0	0.1	0.6	-0.04

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	0.018	0.015	0	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.037	-	0.025	0.015	0	1	0
Sub-Op503	Controlled incincration of other hazardous materials	0	-	0.015	0.025	0	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0.059	-	0.025	0.015	0	1	0
Sub-Op508	Dispose the waste as MWS	0.111	-	0.025	0.015	0	1	0
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.376	-	0.025	0.015	0	1	0.02

Actual Economical Performance = 7.27

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure A5.13: Calculation of actual economical performance of recycling through recycling process plan

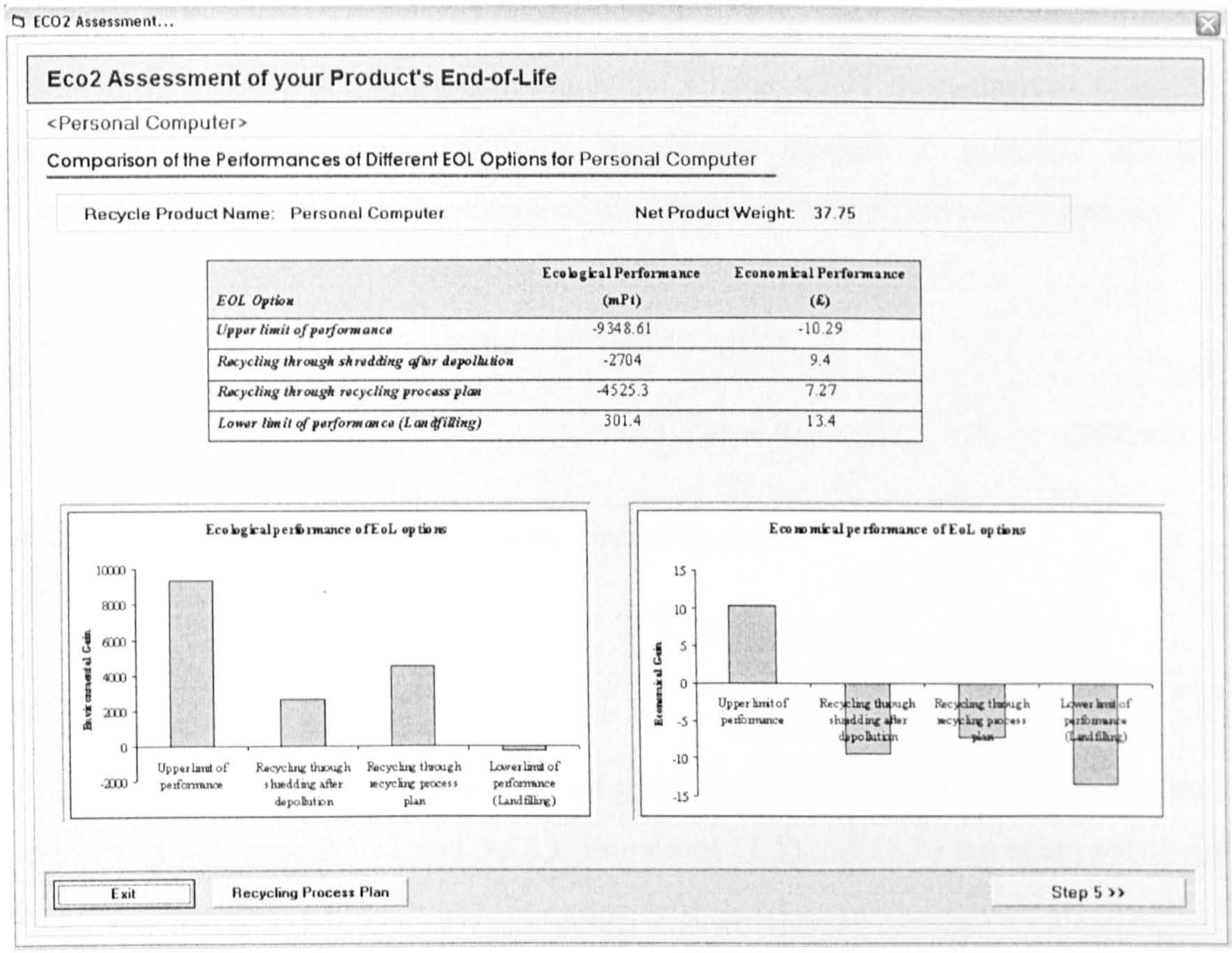


Figure A5.14: Comparison of performances of different end-of-life options for the computer

Figures A5.8 and A5.9 highlights the calculation of the ecological and economical performance limits for the computer. Equations (8.1) and (8.3) (see section 8.4.3) are used to calculate ecological performance limits for the computer.

$$\textit{Upper limit of ecological performance} = BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) = \textit{-9348.6mPt}$$

$$\textit{Lower limit of ecological performance} = WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) = \textit{301.4mPt}$$

Similarly, Equations (8.2) and (8.4) are used to calculate the economical performance limits.

$$\textit{Upper limit of economical performance} = BCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{BCS}) = \textit{- £10.29}$$

$$\textit{Lower limit of economical performance} = WCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{WCS}) = \textit{£13.4}$$

The calculation of the actual performance of shredding option within the assessment module of the CA*R*PP is illustrated in Figure A5.10 and A5.11. Equations (8.5) and (8.6) (see section 8.4.4) are used within the assessment module to calculate the actual ecological and economical performance of the computer through shredding option.

Actual ecological performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -2704mPt$$

Actual economical performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £9.4$$

Similarly, the calculation of the actual performance of the recycling process plan option is illustrated in Figure A5.12 and A5.13. Equations (8.5) and (8.6) are again used within the assessment module to calculate the actual ecological and economical performance for the computer through recycling process plan option.

Actual ecological performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = -4125.3mPt$$

Actual economical performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £7.27$$

Finally, the combined Eco^2 performance ratios of different end-of-life options providing an overview of their ecological and economical performances are calculated. The upper and lower performance limits for the computer are:

- Upper ecological performance limit BCS_{ecol} = -9348.61 mPt
- Lower ecological performance limit WCS_{ecol} = 301.4 mPt
- Upper economical performance limit BCS_{econ} = -£10.29
- Lower economical performance limit WCS_{econ} = £13.4

The actual ecological and economical performances of recycling of the computer through 'shredding after depollution' are:

- Actual ecological performance AP_{ecol} = -2704 mPt
- Actual economical performance AP_{econ} = £9.4

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for shredding after depollution.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-2704 - 301.4}{-9348.61 - 301.4} = 0.312$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{9.4 - 13.4}{-10.29 - 13.4} = 0.17$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.312 + 0.17}{2} = 0.241$$

Similarly, the actual ecological and economical performances of recycling of the computer through 'recycling process plan option' are:

- Actual ecological performance AP_{ecol} = -4525.3 mPt
- Actual economical performance AP_{econ} = £7.27

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for recycling process plan option.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-4525.3 - 301.4}{-9348.61 - 301.4} = 0.501$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{7.27 - 13.4}{-10.29 - 13.4} = 0.26$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.501 + 0.26}{2} = 0.38$$

As C***E***PR ranges from '0' to '1', with '0' being the lower performance limit (worst case scenario) and '1' being the upper performance limit (best case scenario) (see section 8.4.6 for these calculations), the higher value of C***E***PR (close to 1) represents a good overall performance of the assessed end-of-life option. Hence, it can be concluded that the overall performance of the recycling process plan option (C***E***PR = 0.38) is better than the shredding after depollution option (C***E***PR = 0.241) for the computer as depicted in Figure A5.15

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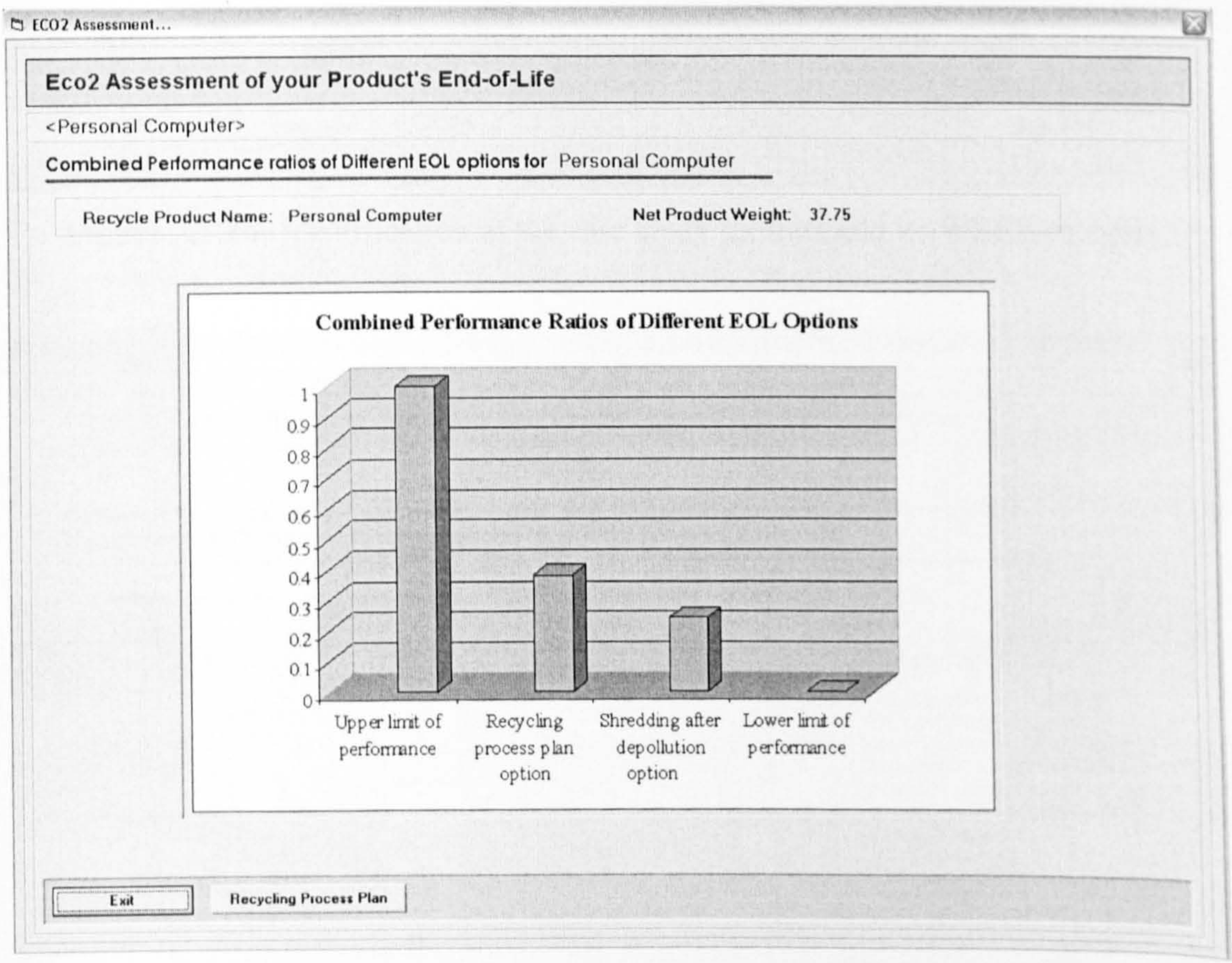

Figure A5.15: Overall ranking of different end-of-life options for the computer

A5.2.1 Product Evaluation for Electric Kettle

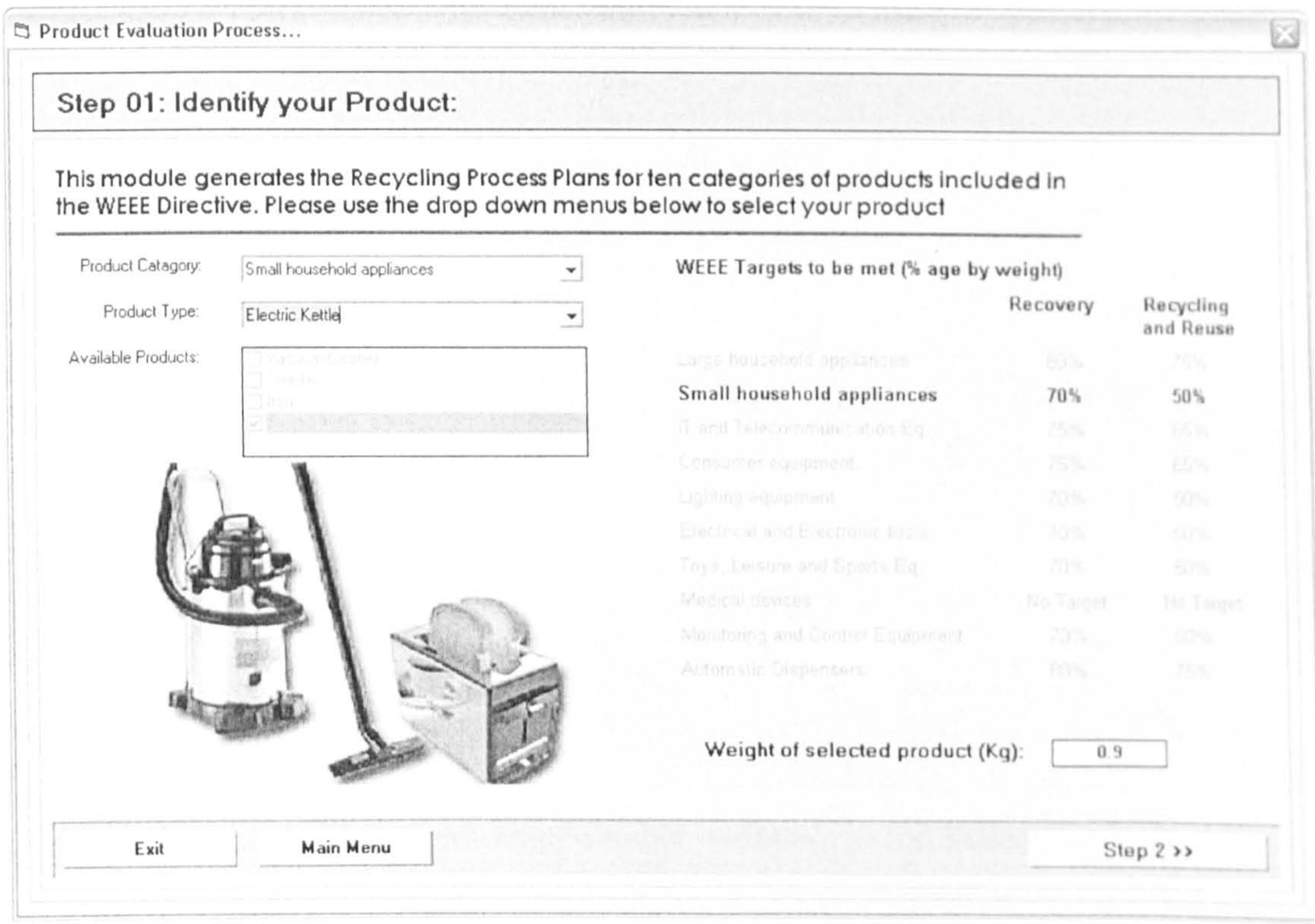

Figure A5.16: Identification of the case study product and its WEEE category

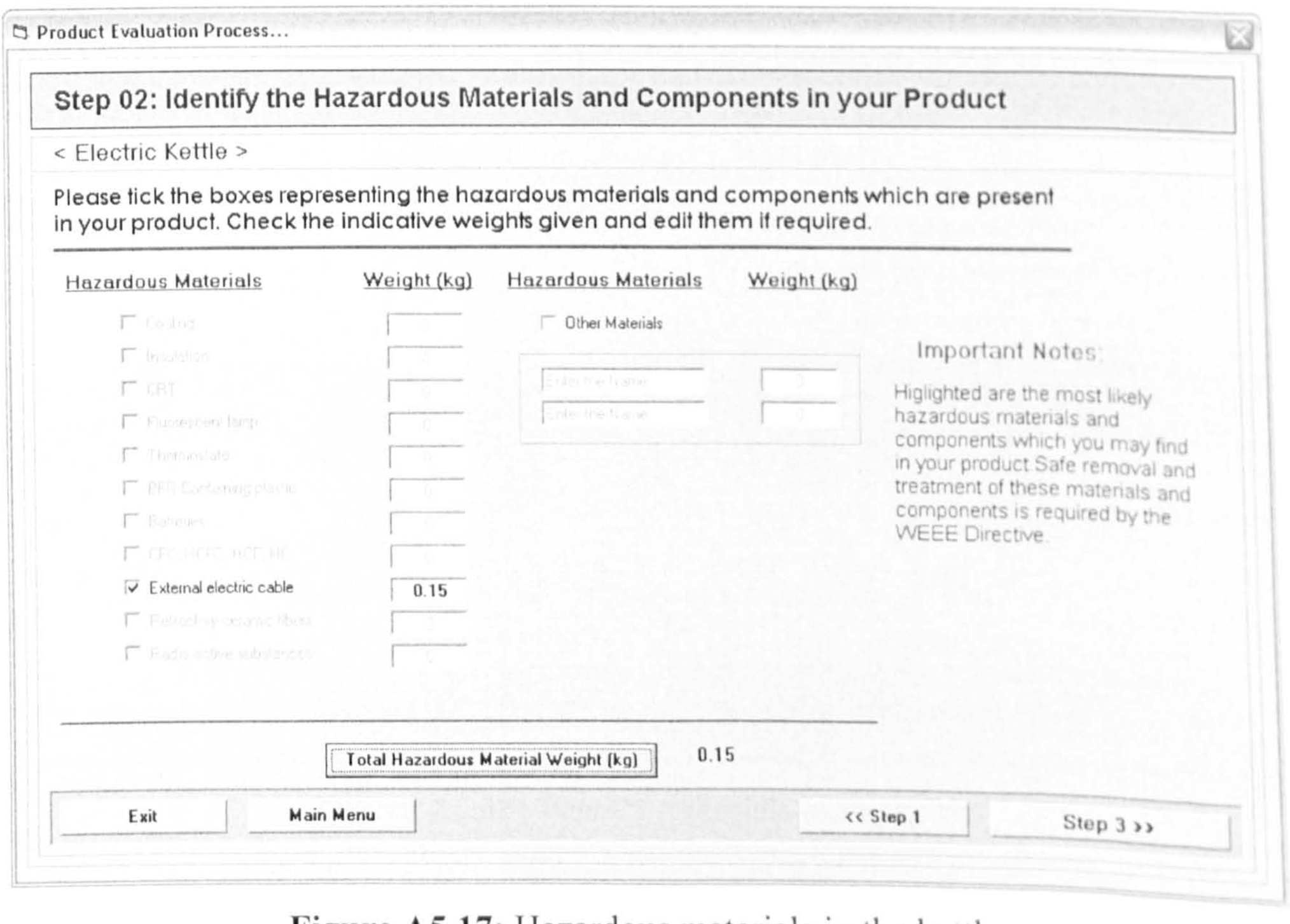

Figure A5.17: Hazardous materials in the kettle

Product Evaluation Process...

Step 03: Identify the Valuable Materials and Components in your Product

< Electric Kettle >

Please tick the boxes representing the valuable materials and components which are present in your product. Check the indicative weights given and edit them if required.

Valuable Materials	Weight (kg)	Valuable Materials	Weight (kg)
☐ Aluminium	0	☐ Other Materials	
☐ ICs	0	Enter the Name	0
☐ Processor	0	Enter the Name	0
☐ Modem	0		
☐ Network Card	0		
☐ Memory	0		
☐ Motor	0		
☐ Compressor	0		
☐ Power Supply	0		
☐ LCD	0		
☐ Transformer	0		
☐ Heating Element	0		

Total Valuable Material Weight (kg) 0

Exit | Main Menu | << Step 2 | Step 4 >>

Important Notes:

Highlighted are the most likely valuable materials and components which you may find in your product. These valuable materials and components have a high potential for revenue generation . Safe removal and reuse of these valuable materials and components resutls in positive revenue which helps to make recycling of WEEE economically self-sufficient.

Figure A5.18: Valuable materials in the kettle

Product Evaluation Process...

Step 04: Identify the Penalty Materials and Components in your Product

< Electric Kettle >

Please tick the boxes representing the penalty materials and components which are present in your product. Check the indicative weights given and edit them if required.

Penalty Materials	Weight (kg)	Penalty Materials	Weight (kg)
☐ Concrete	0	☐ Other Materials	
☐ Textile	0	Enter the Name	0
☐ Wood	0	Enter the Name	0
☐ PVC	0		
☐ Copper	0		
☐ Cables	0		

Total Penalty Material Weight (kg) 0

Exit | Main Menu | << Step 3 | Step 5 >>

Important Notes:

Highlighted are the most likely penalty materials and componenets which you may find in your product . These penalty materials and components causes serious problems for post-fragmentation material separation. Removing these penalty materials and components before the product hulk is sent to the shredder is a value-added activity which eliminates the contaminations in shredded material streams.

Figure A5.19: Penalty materials in the kettle

Product Evaluation Process ...

Step 05: Shredding and Material Separation for your Product

< Electric Kettle >

>> Weight of product before shredding (Kg): 0.75

Based on the generic material composition of WEEE the weight of each material type included in your product is calculated below. Check the weights below and edit them if required.

Each material stream is linked to an appropriate material separation process. Separability efficiency of each material separation process is considered before calculating the total material recovered from the product.

Material Type	Composition (weight %)	Weight (kg)	Process Type	Separatability Efficiency	Material Processed	Material Recovered
☑ Iron and steel	0	0	Managatic Separation	0.98	0	0
☑ Flame retarded plastics	0	0	Skin Floatation	0.70	0	0
☑ Non-Flame retarded plastics	74.9	0.561	Electrostatic Separation	0.65	0.561	0.364
☑ Wood and plywood	0	0	Air Separation	0.85	0	0
☑ Aluminium	0	0	Eddy Current Separation	0.9	0.131	0.117
☑ Copper	3.5	0.026				
☑ Other Metals	14	0.105				
☑ Glass	0	0	Heavy Medium Separation	0.75	0.056	0.042
☑ Rubber	0	0				
☑ Concret and ceramics	4	0.03				
☑ Others	3.5	0.026				

Recalculate

Total Material Recovered: 0.523

Exit | Main Menu | << Step 4 | Step 6 >>

Figure A5.20: Composition and post fragmentation separation of the kettle

Product Evaluation Process ...

Step 06: Identify Safe Disposal for your Product

< Electric Kettle >

Inefficiencies of the material separation processes and economics of available recycling technologies necessitate safe disposal of the shredder residue. Certain hazardous substances removed from WEEE also require safe disposal.

Weight of the Product to be disposed (kg) 0.227

Disposal suitable for landfill	Weight (kg)
☑ Controlled landfill of Skin floatation process waste	0
☑ Dispose the waste as MWS	0.002

Disposal suitable for Incineration	Weight (kg)
☑ Controlled Incineration of Electrostatic seperation waste	0.145
☑ Incinerate Air separation process fluff	0
☑ Incinerate Heavy medium separation process fluff	0.008
☑ Controlled incincration of other hazardous materials	0

Important Notes:

Incineration of WEEE can result in high concentration of metals, heavy metals in the slag, the flue gas or the filter cakes. Care is to be taken to dispose certain materials included in the WEEE which are not suitable for incineration in view of the hazardous nature of the flue gas residues and are better to be sent to controlled landfill.

Exit | Main Menu | << Step 5 | Generate Recycling Process Plan

Figure A5.21: Safe disposal of the kettle hulk

Recycling Process Plan...

Step 07: Recycling Process Plan for your Product

The Recycling process plan for: < Electric Kettle >

Recycle Product Name:	Electric Kettle
Recycle Product Category:	Small household appliances
Net Product Weight:	0.9
Total Hazardous Material Weight(kg):	0.15
Weight Sent to Shredder(kg):	0.75
Weight disposed as MWS(kg):	0.145

Process ID | Process Description | Weight Processed

OP100 Depollution for legislative compliance:

Sub-Op109	Remove External electric cable for Material Recovery	0.15

OP200 Valuable parts recovery:

Process ID | Process Description | Weight Processed

OP300 Dismantling to remove Penalty substances:

OP400 Shredding and Mechanical Separation:

Sub-Op402	Use Air Separation to recover lighter fractions	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	0
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.117
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.042
Sub-Op409	Use Skin Floatation to recover FR plastics	0
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.364

OP500 Safe Disposal:

Sub-Op501	Incinerate Air separation process fluff	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.008
Sub-Op503	Controlled incincration of other hazardous materials	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0
Sub-Op508	Dispose the waste as MWS	0.002
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.145

Weight of the Product Recycled	0.523
Weight of the Product Recovered	0.676

Compliance Monitor

Electric Kettle	Recovery (%)	Recycling (%)
Targets	70	50
Achieved	75.11	58.11
Compliance	Yes	Yes

Exit | Save Recycling Process Plan | Environmental Assessment of Recycling Process Plan >>

Figure A5.22: Bespoke recycling process plan for the kettle

A5.2.2 Ecological and Economical Assessment of Electric Kettle

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Electric Kettle >

Upper and Lower Limits of Environmental Performance for < Electric Kettle >

Recycle Product Name: < Electric Kettle > **Net Product Weight:** 0.9

An upper and lower limit of end-of-life Environmental Performance is calculated to evaluate the environmental performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg)		mi x Eli bcs (mPt)	mi x Eli wcs (mPt)
		Material Substitution (Eli bcs)	Landfill (Eli wcs)		
Steel	0	-86	1.4	0	0
FR Plastics	0	-383.3	3.95	0	0
NFR Plastics	0.64	-383.3	3.95	-245.31	2.53
Wood / Plywood	0	-39	4.2	0	0
Aluminium	0	-780	1.4	0	0
Copper	0.1	-1400	1.4	-140	0.14
Other metals	0.1	-1150.9	1.4	-115.09	0.14
Glass	0	-66	1.4	0	0
Rubber	0	-360	7.4	0	0
Concrete	0.03	-3.8	1.4	-0.11	0.04
Others	0.02	-100	1.4	-2	0.03

Upper limit of Ecological Performance = -502.51

Lower limit of Ecological Performance = 5.85

Upper limit of environmental performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any environmental burden of treatment processes."

Lower limit of environmental performance is calaculated considering that every material in the Product is ending up in the landfill without any environmental burden of treatment processes."

Exit | Recycling Process Plan | Step 2 >>

Figure A5.23: Calculation of the ecological performance limits

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Electric Kettle >

Upper and Lower Limits of Economical Performance for < Electric Kettle >

Recycle Product Name: < Electric Kettle > **Net Product Weight:** 0.9

An upper and lower limit of end-of-life Economical Performance is calculated to evaluate the economical performance of the proposed recycling process plan.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg)		mi x Cli bcs (£)	mi x Cli wcs (£)
		Material Revenue (Cli bcs)	Disposal Cost (Cli wcs)		
Steel	0	0.07	0.03	0	0
FR Plastics	0	0.1	0.03	0	0
NFR Plastics	0.64	0.1	0.05	0.06	0.03
Wood / Plywood	0	0	0.03	0	0
Aluminium	0	0.8	0.03	0	0
Copper	0.1	2.8	0.03	0.28	0
Other metals	0.1	0.1	0.03	0.01	0
Glass	0	0.03	0.04	0	0
Rubber	0	0.1	0.03	0	0
Concrete	0.03	0	0.03	0	0
Others	0.02	0	0.08	0	0

Upper limit of Economical Performance = -0.35

Lower limit of Economical Performance = 0.53

Cost of Depollution = 0.5

Upper limit of economical performance is calaculated considering that every material in the Product is recovered in its initial amount and grade without any economical burden of treatment processes."

Lower limit of economical performance is calaculated considering that every material in the Product is ending up in the landfill."

Exit | Recycling Process Plan | Step 2 >>

Figure A5.24: Calculation of the economical performance limits

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Electric Kettle >

Environmental Impact Assessment of the current recycling practice for < Electric Kettle >

Recycle Product Name: < Electric Kettle > Hazardous Materials Weight: 0.15 Shredding Weight: 0.75

End-of-life environmental performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) (Eli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
		Material Substitution	Landfill	Incineration			
Steel	0	-86	-	-	0.95	0.8	0
FR Plastics	0	-	3.95	-	1	1	0
NFR Plastics	0.53	-383.3	-	-	0.70	0.6	-85.32
Wood / Plywood	0	-	-	-12	1	1	0
Aluminium	0	-780	-	-	0.85	0.65	0
Copper	0.09	-1400	-	-	0.85	0.7	-74.97
Other metals	0.09	-	-	-32	1	1	-2.88
Glass	0	-	1.4	-	1	1	0
Rubber	0	-	7.4	-	1	1	0
Concrete	0.02	-	1.4	-	1	1	0.03
Others	0.02	-	1.4	-	1	1	0.03

Actual Ecological Performance = -160.14

Exit | Recycling Process Plan | Step 3 >>

Figure A5.25: Calculation of actual ecological performance through shredding

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Electric Kettle >

Economical Impact Assessment of the current recycling practice for < Electric Kettle >

Recycle Product Name: < Electric Kettle > Hazardous Materials Weight: 0.15 Shredding Weight: 0.75

End-of-life economical performance of the current state-of-the-art takes into consideration material ending up at different end-of-life stages (Material recovery, Energy Recovery, Landfill, Leakage to environment) and is calculated below.

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)			Process Efficiency (PEi)	Grade (Gi)	mi x Cli ap x PEi x Gi (£)
		Processing Cost	Disposal Cost	Material Revenue			
Steel	0	0.02	-	0.07	0.95	0.8	0
FR Plastics	0	0.025	0.015	-	1	1	0
NFR Plastics	0.53	0.025	-	0.1	0.70	0.6	-0.02
Wood / Plywood	0	0.018	0.015	-	1	1	0
Aluminium	0	0.028	-	0.8	0.85	0.65	0
Copper	0.09	0.030	-	2.8	0.85	0.7	-0.15
Other metals	0.09	0.030	0.015	-	1	1	0
Glass	0	0.024	0.04	-	1	1	0
Rubber	0	0.024	0.015	-	1	1	0
Concrete	0.02	0.015	0.015	-	1	1	0
Others	0.02	0.015	0.08	-	1	1	0

Actual Economical Performance = -0.17

Cost of Depollution = 0.5

Exit | Recycling Process Plan | Step 3 >>

Figure A5.26: Calculation of actual economical performance through shredding

ECO2 Assessment...

Environmental Assessment of your Product's End-of-Life

< Electric Kettle >

Environmental Impact Assessment of the Proposed Recycling Process Plan for < Electric Kettle >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Environmental Impact (mPt/kg) (Eli ap)				Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
			Material Substitution	Landfill	Incineration	Actual		
Sub-Op109	Remove External electric cable for Material Recovery	0.15	-891.6	2.67	-82.7	-891.6	0.75	-100.3

Valuable Recovery

Penalty Removal

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-39	4.2	-12	-12	0.75	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	0	-86	1.4	-32	-86	0.8	0
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.117	-992.9	1.4	-110	-992.9	0.65	-75.51
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.042	-99	2.6	6.77	-99	0.6	-2.49
Sub-Op409	Use Skin Floatation to recover FR plastics	0	-383.4	3.95	37	3.85	0.6	0
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.364	-383.4	3.95	-13	-383.3	0.6	-83.71

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	4.2	-12	-12	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.008	-	2.6	6.77	6.77	1	0.05
Sub-Op503	Controlled incincration of other hazardous materials	0	-	7.83	-20.8	-20.8	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0	-	3.95	37	3.95	1	0
Sub-Op508	Dispose the waste as MWS	0.002	-	1.4	-15	-15	1	-0.03
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.145	-	3.95	-13	-13	1	-1.88

Actual Ecological Performance = -263.87

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure A5.27: Calculation of actual ecological performance of recycling through recycling process plan

ECO2 Assessment...

Economical Assessment of your Product's End-of-Life

< Electric Kettle >

Economical Impacts Assessment of the Proposed Recycling Process Plan for < Electric Kettle >

Depollution

Process ID	Process Description	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap)				Grade (Gi)	mi x Cli ap x PEi x Gi (£)
			Disassembly Cost	Processing Cost	Disposal Cost	Material Revenue		
Sub-Op109	Remove External electric cable for Material Recovery	0.15	0.4	0.015	-	1.1	0.75	0.28

Valuable Recovery

Penalty Removal

Shredding and Mechanical Separation

Sub-Op402	Use Air Separation to recover lighter fractions	0	-	0.018	0.015	0	1	0
Sub-Op403	Use Managatic Separation to recover ferrous metals	0	-	0.02	0	0.07	0.8	0
Sub-Op405	Use Eddy Current Separation to recover non-ferrous metals	0.117	-	0.03	0	1.48	0.65	-0.11
Sub-Op406	Use Heavy Mediam Separation to recover heavies	0.042	-	0.025	0.015	0	1	0
Sub-Op409	Use Skin Floatation to recover FR plastics	0	-	0.025	0.015	0	1	0
Sub-Op410	Use Electrostatic Separation to recover non-FR plastics	0.364	-	0.025	0	0.1	0.6	-0.02

Safe Disposal

Sub-Op501	Incinerate Air separation process fluff	0	-	0.018	0.015	0	1	0
Sub-Op502	Incinerate Heavy medium separation process fluff	0.008	-	0.025	0.015	0	1	0
Sub-Op503	Controlled incincration of other hazardous materials	0	-	0.015	0.025	0	1	0
Sub-Op506	Controlled landfill of Skin floatation process waste	0	-	0.025	0.015	0	1	0
Sub-Op508	Dispose the waste as MWS	0.002	-	0.025	0.015	0	1	0
Sub-Op509	Controlled Incineration of Electrostatic seperation waste	0.145	-	0.025	0.015	0	1	0.01

Actual Economical Performance = 0.16

Exit | Recycling Process Plan | << Step 2 | Step 4 >>

Figure A5.28: Calculation of actual economical performance of recycling through recycling process plan

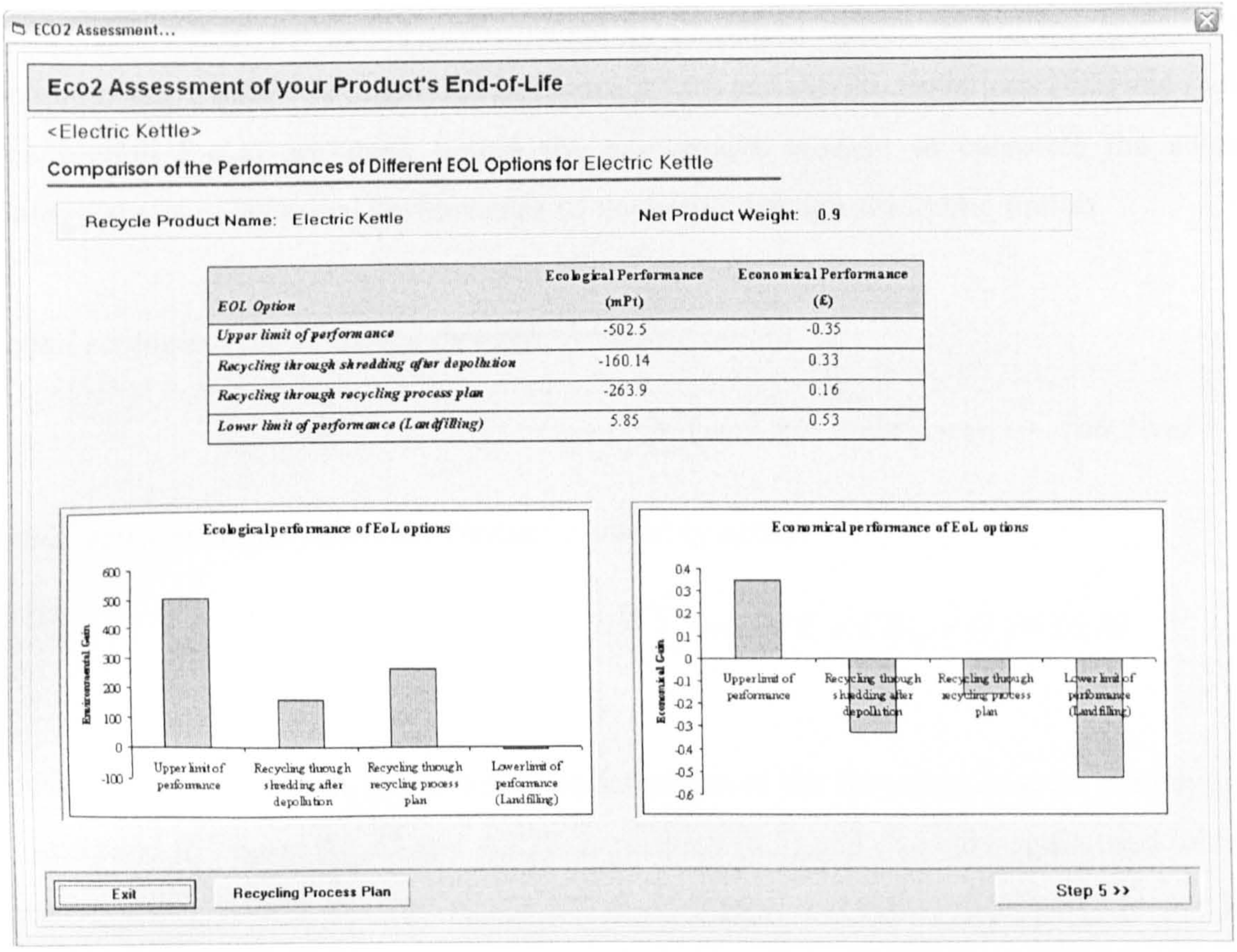

Figure A5.29: Comparison of performances of different end-of-life options for the kettle

Figures A5.23 and A5.24 highlights the calculation of the ecological and economical performance limits for the kettle. Equations (8.1) and (8.3) (see section 8.4.3) are used to calculate ecological performance limits for the kettle.

$$\textit{Upper limit of ecological performance} = BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) = \textit{-502.5mPt}$$

$$\textit{Lower limit of ecological performance} = WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) = \textit{5.85mPt}$$

Similarly, Equations (8.2) and (8.4) are used to calculate the economical performance limits.

$$\textit{Upper limit of economical performance} = BCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{BCS}) = \textit{- £0.35}$$

$$\textit{Lower limit of economical performance} = WCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{WCS}) = \textit{£0.53}$$

The calculation of the actual performance of shredding option within the assessment module of the CA*R*PP is illustrated in Figure A5.25 and A5.26. Equations (8.5) and (8.6) (see section 8.4.4) are used within the assessment module to calculate the actual ecological and economical performance of the kettle through shredding option.

Actual ecological performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = \text{-}160.14mPt$$

Actual economical performance through shredding option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £0.33$$

Similarly, the calculation of the actual performance of the recycling process plan option is illustrated in Figure A5.27 and A5.28. Equations (8.5) and (8.6) are again used within the assessment module to calculate the actual ecological and economical performance for the kettle through recycling process plan option.

Actual ecological performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) = \text{-}\ 263.9mPt$$

Actual economical performance through recycling process plan option

$$= \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) = £0.16$$

Finally, the combined Eco^2 performance ratios of different end-of-life options providing an overview of their ecological and economical performances are calculated. The upper and lower performance limits for the kettle are:

- Upper ecological performance limit BCS_{ecol} = -502.5 mPt
- Lower ecological performance limit WCS_{ecol} = 5.85 mPt
- Upper economical performance limit BCS_{econ} = -£0.35
- Lower economical performance limit WCS_{econ} = £0.53

The actual ecological and economical performances of recycling of the kettle through 'shredding after depollution' are:

- Actual ecological performance AP_{ecol} = -160.14 mPt
- Actual economical performance AP_{econ} = £0.33

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for shredding after depollution.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-160.14 - 5.85}{-502.5 - 5.85} = 0.327$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{0.33 - 0.53}{-0.35 - 0.53} = 0.228$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.327 + 0.228}{2} = 0.277$$

Similarly, the actual ecological and economical performances of recycling of the kettle through 'recycling process plan option' are:

- Actual ecological performance AP_{ecol} = -263.9 mPt
- Actual economical performance AP_{econ} = £0.16

Equation (8.7) and (8.8) are used to calculate the normalised ecological and economical performance ratios for recycling process plan option.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} = \frac{-263.9 - 5.85}{-502.5 - 5.85} = 0.531$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} = \frac{0.16 - 0.53}{-0.35 - 0.53} = 0.421$$

Finally, Equation (8.9) is used to calculate the combined Eco^2 performance ratio

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} = \frac{0.531 + 0.421}{2} = 0.476$$

As C***E***PR ranges from '0' to '1', with '0' being the lower performance limit (worst case scenario) and '1' being the upper performance limit (best case scenario) (see section 8.4.6 for these calculations), the higher value of C***E***PR (close to 1) represents a good overall performance of the assessed end-of-life option. Hence, it can be concluded that the overall performance of the recycling process plan option (C***E***PR = 0.476) is better than the shredding after depollution option (C***E***PR = 0.277) for the kettle as depicted in Figure A5.15

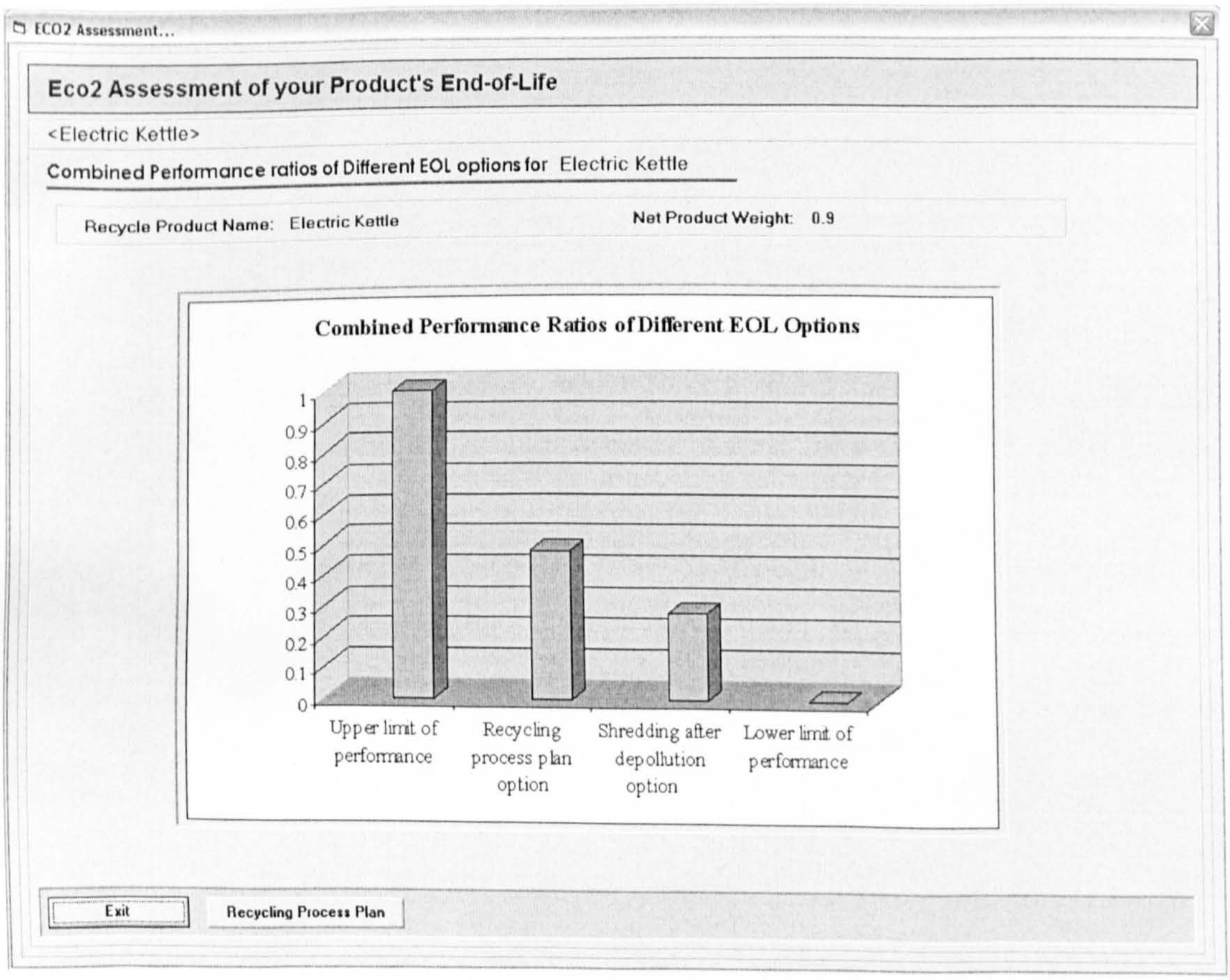

Figure A5.30: Overall ranking of different end-of-life options for the kettle