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Technological innovation and shorter product life cycles of electrical and electronic equipment coupled with their rapidly growing applications have resulted in the generation of an enormous amount of waste from electrical and electronic equipment (WEEE). To address the potential environmental problems that could stem from improper end-of-life management of WEEE, many countries have drafted national legislation to improve the reuse, remanufacture and material recycling from WEEE, and to reduce the amount of such waste going to landfills. With the introduction of such legislation comes an increased need for the recovery operators to evaluate the recycling costs and environmental benefits of reclaimed products and materials in order to select the most appropriate end-of-life options for individual products in WEEE. This paper presents a systematic methodology for ecological and economical assessment to provide a holistic understanding of the impacts associated with different end-of-life options for such waste. This assessment, in addition to providing decision-support for the selection of the best possible end-of-life option for a particular product in WEEE, could also generate vital information to support the design and material selection processes during the initial product development activities. The assertion made is that the detailed considerations of the ecological and economical impacts associated with different end-of-life options will significantly improve the recovery and recycling of WEEE.

Keywords: WEEE; ecological assessment; economical assessment; electrical and electronic equipment; recycling

1. Introduction

The end-of-life (EoL) management of waste from electrical and electronic equipment (WEEE) is attracting significant interest from authorities, consumers and producers. The amount of WEEE generated each year is increasing at an alarming rate along with the environmental problems resulting from the huge amounts of such waste currently arriving at landfills. Studies conducted in Europe estimate that the quantity of WEEE is increasing three times faster than the increase in the general municipal waste stream (Snowdon *et al.* 2000, Turbini *et al.* 2001, Alec 2002). Disposal of WEEE poses a problem not only as a result of the potentially recyclable materials contained in WEEE filling up the scarce landfill capacity but also because of the hazardous nature of its contents. These concerns have resulted in the introduction of the European WEEE Directive, which follows the principle of extended producer responsibility making manufacturers (and at times the retailers) responsible for the take-back, recycling and final disposal of their products. The scope of the WEEE Directive includes 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 EoL phase of WEEE (The European Commission 2003).

The EoL treatment of WEEE can be dealt with in different ways. Generally, there are six alternative EoL options available for a product at its EoL, as depicted in Figure 1. Prevention of the waste creation is always the top priority of any waste management solution. Reduction of waste (also referred to as waste minimisation) aims to generate less waste through efficient use of materials and improved design (Monkhouse and Farmer 2003). Dematerialisation and a move towards services instead of products, referred to as 'Product-Service System' (PSS), offers potential for significant sustainability benefit (Evans *et al.* 2007). The second preferred option in the waste management hierarchy is to reuse the products with minimal requirement for further processing. Reuse includes any operation through which products and components are used for the same purpose they were conceived of in the first place. Recycling of the product for material recovery is the third preferred option. Energy recovery or incineration of waste comes after product recycling for material recovery, however it is less favourable due to potential loss of the material as a

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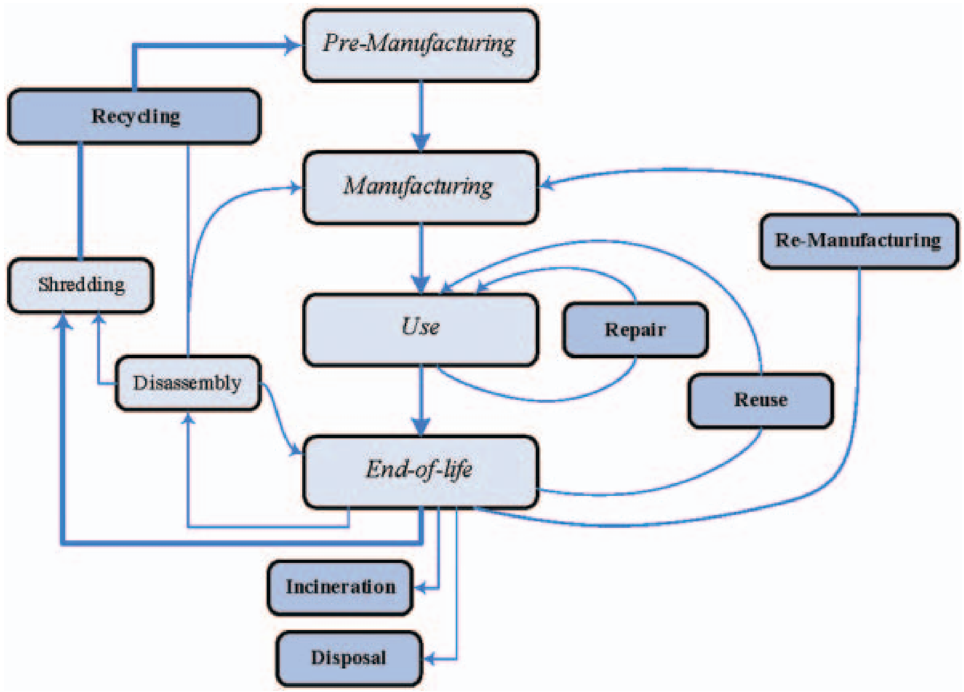


Figure 1. End-of-life options and their relation to product life cycle.

resource and the possible release of toxic gases into the environment. However, recent advances in incineration technologies have significantly reduced the release of harmful gases into the atmosphere.. Finally, disposal of the product in landfill is considered as the worst waste management option. In order to determine the best waste management option for a particular product, a detailed assessment is required to consider different aspects of ecological and economical impacts associated with each option.

Historically in the UK, the recovery treatment of WEEE has mainly been driven by economical considerations without any assessment of the environmental impacts of such recycling activities. The authors argue that selection of the most appropriate EoL option for product recycling should not only be based on economic considerations, but also should take environmental impacts into consideration as this is being imposed by an increase in constraining legislation and green pressure.

The research reported in this paper identifies a holistic approach that combines the Ecological and Economical (Eco^2) assessment of WEEE recycling activities considering different EoL processing and recovery options. It is envisaged that the concurrent analysis of the environmental impacts and the cost of recovery and recycling activities can help the recyclers (and also policy makers) to significantly improve the selection of the most appropriate EoL options for WEEE. The initial sections of the paper introduce the background to the research, including a review of the most relevant literature as well as an overview of the current WEEE recovery chain in the UK. The latter sections of the paper present a methodology for ecological and economical assessment as well as various tasks involved in the Eco^2 assessment methodology. The paper concludes by providing a computational viewpoint of the Eco^2 assessment using a case study product, namely a household refrigerator.

2. Review of relevant literature

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 EoL management. This is especially true for products where the EoL stage has high environmental and economical impact. The selection of an appropriate EoL option for treating a product at the end of its life is influenced by several decision factors. These factors include the level of disassembly, sequencing for dismantling operations, and the available EoL options together with their ecological and economical impacts.

A major focus of EoL research effort is the field of disassembly as this plays a key role in the economics of product recycling. Penev and de Ron (1996) describe a cost modelling tool to determine an economic disassembly level and disassembly sequence. Lambert (1997) developed a linear optimisation model for optimal disassembly of complex products. Disassembly is not only essential to ensure the required purity of recycled materials so that they can be accepted by material merchants (Wiendahl *et al.* 1999) but is also needed to extract components and subassemblies of interest for repair, reuse or remanufacturing (Salomonski and Zussman 1999). Johnson and Wang (1995) suggest an algorithm to maximise the profit involved in material recovery opportunities. Pnueli and Zussman (1997) also present a dynamic programming algorithm to solve the disassembly sequencing problem that includes the EoL value of a product.

For a given EoL 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 planning as well as product recovery and recycling planning. With regard to decision-support at EoL, some studies have incorporated both cost estimation and environmental impact estimation. However, these studies mainly provide an assessment at the macro level. For example, Krikke *et al.* (1998) describe a method on a tactical management level to determine an optimal recovery and disposal strategy of product type considering technical, economical and ecological criteria. Yu *et al.* (2000) adopted an analytical hierarchic process to find the best recycling strategy in which environmental impact, cost and reclaimed materials are considered as the major criteria for strategy selection. Lamvik *et al.* (2002) presented '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 EoL 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 EoL scenario but lacks operational support required for EoL product recovery for the complex WEEE stream. 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. The QWERTY approach considers the environmental value of secondary materials and the environmental burden of the EoL treatment itself. Although the QWERTY approach is quite powerful in assessing the effectiveness of EoL processing and the impact of product design on recyclability issues, it does not provide the operational support to enable a typical recycler to identify the best EoL recovery and recycling processes for WEEE. Herrmann *et al.* (2002) also describe a method to calculate economical and ecological indicators to evaluate recycling of material within electrical and electronic waste, utilising life-cycle assessment (LCA) and life-cycle costing to calculate these indicators. This assessment approach only focuses on the material recycling option and excludes the consideration of other options in waste hierarchy, e.g. reuse, remanufacture, incineration, etc. Furthermore, in this approach the resulting two indicators need to be further interpreted and assessed against each other to reach a final decision. The methodology presented in this paper is unique in that it provides a simple but effective process to calculate the ecological and economical impacts of various EoL options for WEEE and combines them in the form of a single ratio which is easier to interpret than the conventional results obtained from an LCA and life-cycle costing. This provides a holistic assessment to support the decision in selecting the most appropriate EoL route for a specific product in WEEE.

3. An overview of the current recovery chain for WEEE in the UK

Most WEEE originates from three sources: firstly the domestic end-users with household WEEE; secondly the commercial end-users with business WEEE; and thirdly the manufacturers, distributors, and retailers with ex-lease products, excess inventory, customers' returns and obsolete assets. The EoL activities for WEEE generally include collection, transportation, storage, pre-treatment (removal of hazardous substances), treatment (refurbishing, disassembly, shredding) and recycling (material recovery) (Cui and Forssberg 2003). Historically in the UK, the metal dominated products (white goods) have been targeted for material 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 metals without any consideration to the environmental impact of substantial quantities of untreated shredder residue waste being sent to landfill sites. Furthermore, the current recovery treatment of WEEE 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.

The WEEE regulations in the UK introduced a new system from 1 July 2007 in accordance with the requirements of the European WEEE directive (Department of Trade and Industry 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.

However, the majority of commercial end-users and manufacturers 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 EEE 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'. In such an approach, EEE manufacturers can join a compliance scheme to discharge their obligations under WEEE regulations. For collection activity, distributors can choose between in-store take-back or a scheme in which the customers are given free access to a locally operated designated collection facility. Designated collection facilities could be the existing local authority civic amenity sites, independent sites operated by third party, or retailer's platforms established as a result of distributors offering take-back as part of their delivery services to their customers. Designated collection facilities aim to separate the collected 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 designated facilities, and treatment, reprocessing and recovery of used product at approved authorised treatment facilities in accordance with WEEE treatment regulations. Figure 2 shows the main actors in the proposed WEEE recovery chain in the UK.

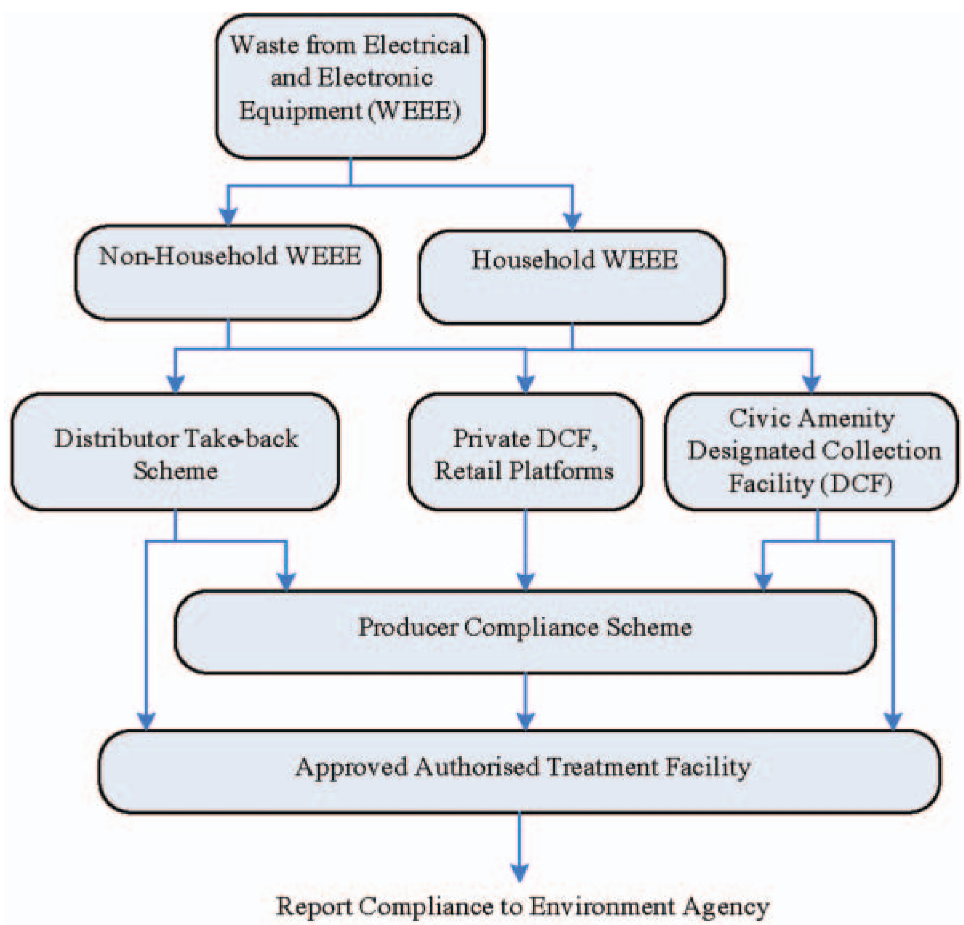


Figure 2. WEEE recovery chain in the UK.

It is argued that the way in which the 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 dependent 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 could have a severe impact on the whole economics of WEEE recovery and recycling. Furthermore, in its current form the WEEE Directive gives equal importance to the recovery and recycling of unit weight of concrete as compared with copper. Hence, the current targets included in the WEEE Directive require re-evaluation based on the actual environmental gain and economical ramifications to provide more meaningful guidelines for the emphasis in WEEE recycling.

It is clear that the WEEE Directive 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 environmentally-friendly. Secondly, it is forcing them to develop and establish a profit making opportunity from WEEE recycling. 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 assessment methodology to aid decision making involved in the selection of the best possible WEEE EoL strategy.

4. Methodology for ecological and economical assessment of WEEE recycling

As stated, an EoL product may be collected and examined for possible refurbishment and reuse, disassembled for material reclamation, incinerated, discarded to landfill, or indeed a combination of these activities may occur. A key problem in the EoL management of WEEE is to determine to what extent return products must be disassembled and which EoL option should be applied while minimising the environmental and economical impacts of product recycling. The Ecological and Economical (Eco^2) assessment methodology presented in this paper is a part of an integrated framework for developing bespoke 'Recycling Process Plans' for various products in WEEE. Further details of the recycling process planning framework is provided elsewhere (Abu Bakar and Rahimifard 2007), while the remaining sections of this paper describe the tasks involved in 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 EoL options for WEEE. In the Eco-indicator 99 methodology (PRE Consultants 2000), which is a damage-oriented LCA method, all environmental effects are translated into actual damage inflicted to eco-system quality, human health and resource depletion; and the final result is expressed in a single score (referred to as a point) that indicates the overall damage to the environment. In cost-benefit analysis, the costs (depollution, part and material recovery, disposal costs, etc.) and the revenues from various EoL options are calculated in order to determine their economical impact. Finally, the results of these ecological and economical assessments are combined in the form of a 'Combined Eco^2 Performance Ratio' which is used in this research to identify the most appropriate EoL options for treating WEEE. Figure 3 provides an overview of the various tasks involved in the Eco^2 assessment methodology which are further described in the following sections.

4.1 *Identification of product material composition*

Both the ecological and economical assessment is heavily dependent on the material composition of the EoL product. The required information about the composition of main materials such as 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. Readers are referred to Abu Bakar and Rahimifard (2008) for further details about the bespoke five-step, product evaluation process which has been developed as part of the recycling process planning framework. The generic material composition data per product category (Taberman *et al.* 1995) is adjusted during the product evaluation to identify both the actual product material composition and the distribution of materials shared between the relevant EoL treatments. Information about different hazardous, valuable and penalty (contaminating) materials and components is also identified through product evaluation which helps to determine the actual ecological and economical performance of different EoL options later in the Eco^2 assessment methodology.

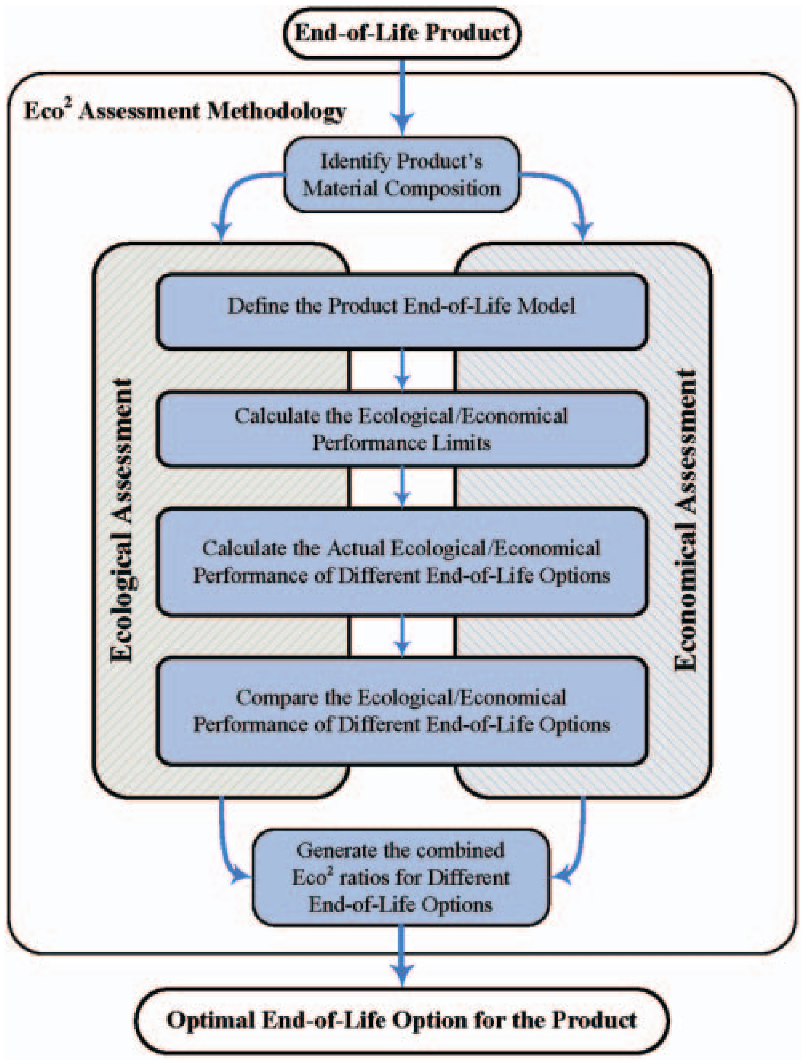


Figure 3. Tasks involved in the Eco^2 assessment methodology.

4.2 *Identification of different EoL options*

The second task in the Eco^2 assessment methodology is the identification of different feasible EoL options for the disposed product. The review of current WEEE applications in the UK has highlighted very limited opportunities for environmentally beneficial and economically justifiable product life extension through remanufacture of EoL products. In addition, a number of studies have highlighted the counterproductive effect of inappropriate remanufacture/reuse applications in terms of energy efficiency, the subsequent EoL stage and the release of toxic substances (Rose *et al.* 1999, Rose 2000, Chalkley *et al.* 2003). Therefore, the EoL options investigated for the case study presented in this paper focus on the current state-of-the-art practice of de-pollution, fragmentation and separation and also assesses the merits of a bespoke approach which involves de-pollution, pre-fragmentation dismantling, fragmentation and separation based on a specific recycling process plan that has been developed for a product (Abu Bakar and Rahimifard 2008). However, the authors believe that the methodology presented could easily be expanded to include a consideration of remanufacturing applications. The Eco^2 assessment methodology considers the following three most commonly adopted EoL options in the refrigerator case study for further assessment:

- recycling through shredding after depollution (Figure 4(a));
- recycling through recycling process plan (Figure 4(b));
- landfilling.

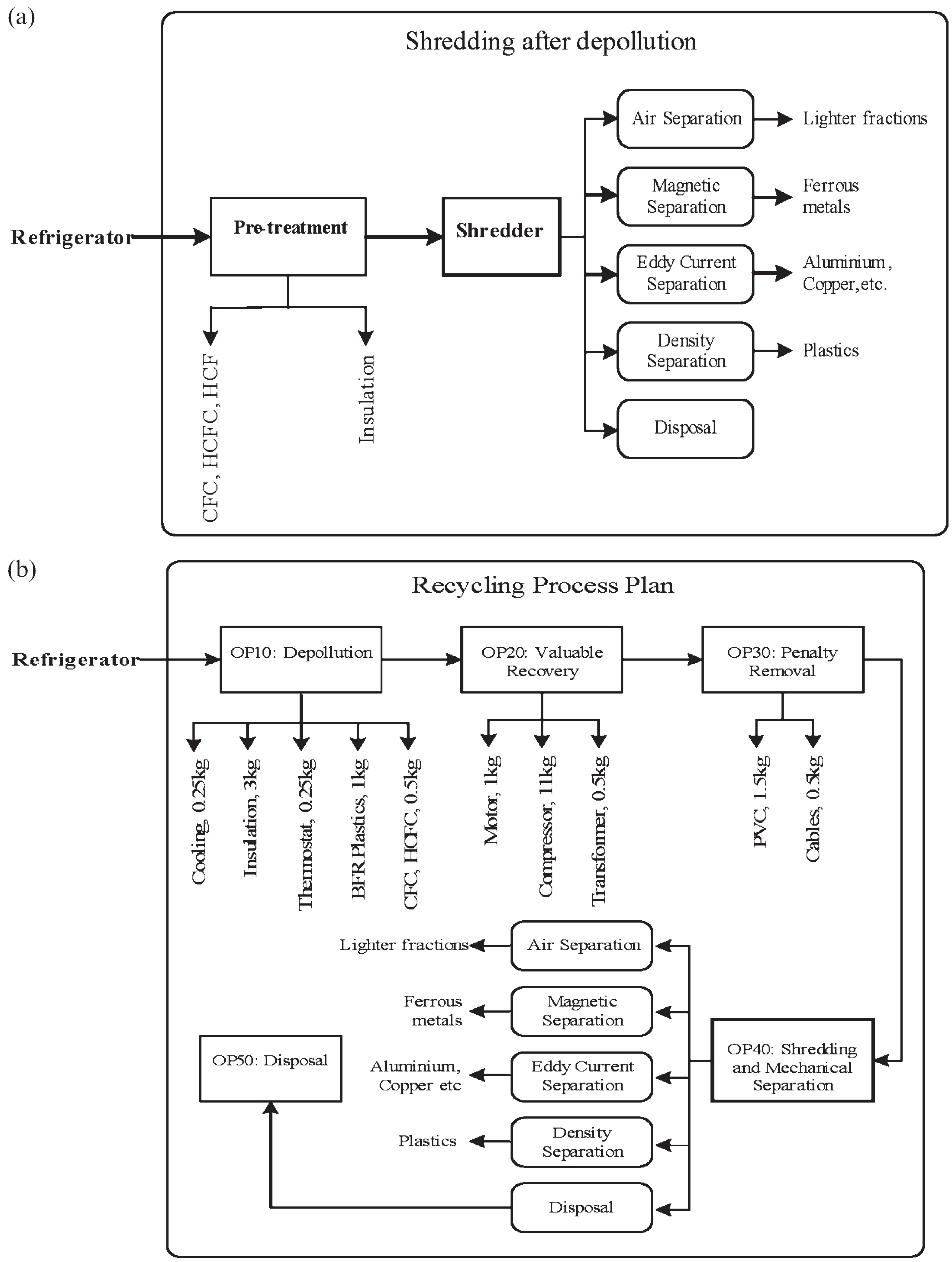


Figure 4. Schematic of different EoL options for a typical electrical and electronic equipment. (a) Recycling through shredding after depollution. (b) Recycling through the recycling process plan.

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 EoL 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 not practicable at present and its theoretical value serves merely as a fixed (upper) point in the evaluation scale, representing a best case scenario (BCS). Equations (1) and (2) are used to calculate the upper limit of ecological and economical performance respectively.

$$BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) \quad (1)$$

$$BCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{BCS}) \quad (2)$$

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^{-1});
CIi_{BCS} is the material revenue of material i in the best case scenario (£ kg^{-1}).

Equation (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 that need 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 referred to as an environmental gain. In a similar way, Equation (2) describes the economical gain through the material revenues of all materials in the product. The actual prices of 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 (3) and (4) are used to calculate the lower limit, representing a worst case scenario (WCS), of ecological and economical performance respectively.

$$WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) \tag{3}$$

$$WCS_{econ} = \sum_{i}^{n} (m_i \times CIi_{WCS}) \tag{4}$$

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^{-1});
CIi_{WCS} is the material revenue value of material i in the worst case scenario (£ kg^{-1}).

Equations (3) and (4) describe the ecological and economical impacts associated with landfilling all materials in the product. The Eco-indicator 99 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.

4.4 *Calculation of the actual performance of different EoL options*

The actual ecological and economical performances of different EoL options are calculated once the upper and lower performance limits are defined. The actual ecological performance (AP_{ecol}) of a specific EoL option of a product under consideration is calculated by Equation (5). Provisions are made for the material degradations and process inefficiencies to be considered while calculating the actual ecological performance associated with different EoL options.

In a similar manner, the actual economical performance (AP_{econ}) of a certain EoL option of a product under consideration is calculated by Equation (6). A parametric cost-benefit analysis approach is used to calculate the actual economical performance of different EoL options of a product under consideration. All respective EoL 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 EoL option.

$$AP_{ecol} = \sum_{i}^{n} (m_i \times PE_i \times EIi_{AP} \times G_i) \tag{5}$$

$$AP_{econ} = \sum_{i}^{n} (m_i \times PE_i \times CIi_{AP} \times G_i) \tag{6}$$

where,

AP_{ecol} is the actual ecological performance of a certain EoL option (mPt);
AP_{econ} is the actual economical performance of a certain EoL 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 EoL route (mPt kg^{-1});
CIi_{AP} is the cost impact of material i in a certain EoL route (£ kg^{-1});

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 those activities related to collection, transportation, storage of WEEE and subsequent material refining processes are not considered.

4.5 *Comparison of the performance of different EoL options*

Once the actual ecological and economical performances associated with different EoL options for a certain product are calculated, they are evaluated in conjunction with the respective upper and lower performance limits. The closer the actual performance is to the upper performance limit (best case scenario) the better is the assessed EoL 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 EoL options.

4.6 *Generation of the combined ratios for ranking different EoL options*

The combined analysis of the ecological and economical assessment data is a necessary task to gain an insight into overall performance of each EoL option. This research has adopted a simple data analysis method which normalises the ecological and economical performance results of different EoL options and then combines them into a 'single ecological and economical performance ratio', referred to as the combined Eco^2 performance ratio. Equations (7) and (8) are used to calculate the normalised ecological performance ratio (EPR_{ecol}) and economical performance ratio (EPR_{econ}) respectively.

$$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}} \tag{7}$$

$$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}} \tag{8}$$

In this paper, the combined Eco^2 performance ratio gives equal importance to both the ecological performance and the economical performance. Equation (9) is used to calculate this combined Eco^2 performance ratio (C*E*PR).

$$CEPR = \frac{EPR_{ecol} + EPR_{econ}}{2} \tag{9}$$

Equations (7) and (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 the upper performance limit will become the 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, Equations (7) and (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 the lower performance limit will become the 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 values of C*E*PR (close to 1) represent a good overall performance of the assessed EoL option. Similarly, lower values of C*E*PR (close to 0) represents a bad overall performance of the assessed EoL option.

5. Case study: Eco^2 assessment of a common household refrigerator

The proposed Eco^2 assessment methodology is applied to evaluate different EoL options for a household refrigerator. The refrigerator is selected as it belongs to large household appliances that make the largest contribution towards the total weight of WEEE in the UK (ICER 2005). It also contains a variety of materials and components including different hazardous, valuable and contaminating materials and will provide a detailed computational viewpoint of the Eco^2 assessment methodology.

5.1 *Material composition of the refrigerator*

Figure 5 lists the material composition of the refrigerator and the distribution of materials over the relevant EoL treatment. This material composition data are based on the generic material composition of WEEE (Taberman *et al.* 1995) and provisions are available to adjust this composition data. Weights of different hazardous, valuable, and penalty materials and components included in the refrigerator are available from the recycling process plan (Figure 6).

5.2 *Different EoL options for the refrigerator*

Three EoL options have been selected for the refrigerator for further assessment. A brief description of each option is given below:

(1) *Recycling through recycling process plan*: this option involves recycling of the refrigerator through a bespoke, five-stage recycling process plan, namely depollution for legislative compliance, valuable parts recovery, dismantling to remove penalty substances, shredding and mechanical separation and safe disposal (see Figure 6).

(2) *Recycling through shredding after depollution*: this option involves shredding the depolluted refrigerator into small fractions and then 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 like insulation, coolant, mercury, etc.

(3) *Landfilling*: this option involves disposal of the complete refrigerator to landfill.

5.3 *Performance limits for the refrigerator*

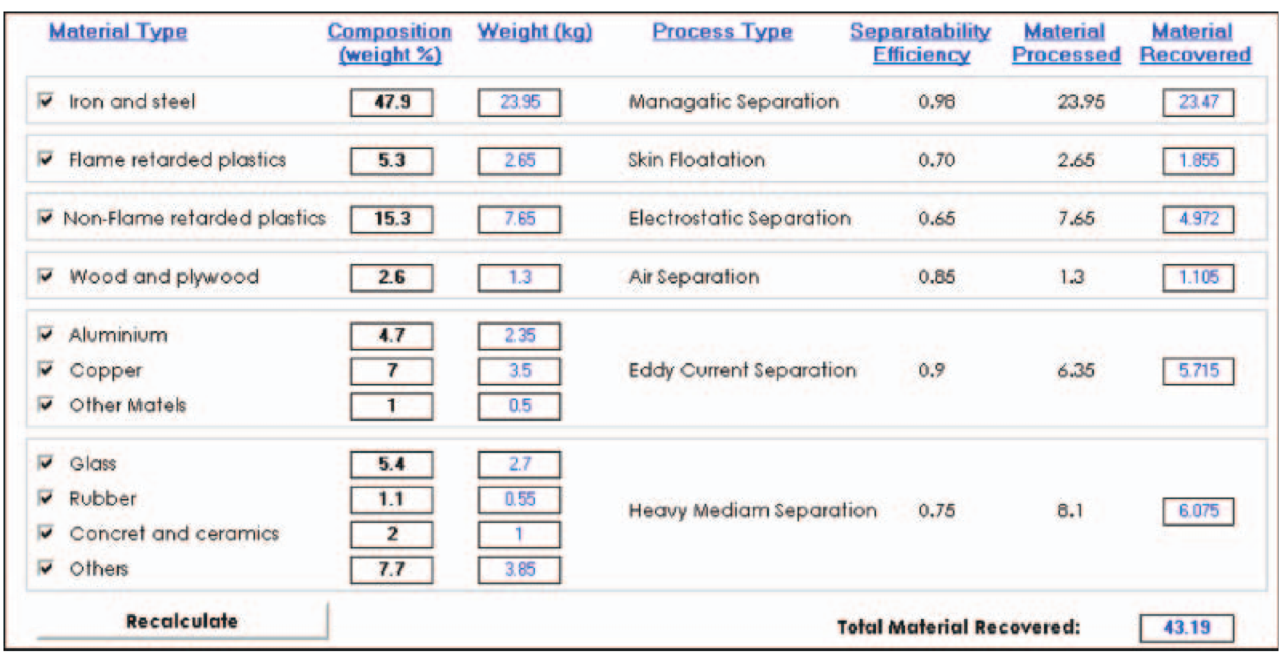
The ecological and economical performance limits for the refrigerator are based on its material composition and are calculated as outlined below and summarised in Figure 7. The performance limits provide a scale for the evaluation and assessment of the actual ecological and economical performance of different EoL 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 (1) and (3) are used to calculate ecological performance limits for the refrigerator (eco-indicator values summarised in Figure 7(a)).

Upper limit of ecological performance

$$= BCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{BCS}) = -14131.84 \text{ mPt}$$

Lower limit of ecological performance

$$= WCS_{ecol} = \sum_{i}^{n} (m_i \times EIi_{WCS}) = 103.21 \text{ mPt}$$



Material Type	Composition (weight %)	Weight (kg)	Process Type	Separatability Efficiency	Material Processed	Material Recovered
Iron and steel	47.9	23.95	Managatic Separation	0.98	23.95	23.47
Flame retarded plastics	5.3	2.65	Skin Floatation	0.70	2.65	1.855
Non-Flame retarded plastics	15.3	7.65	Electrostatic Separation	0.65	7.65	4.972
Wood and plywood	2.6	1.3	Air Separation	0.85	1.3	1.105
Aluminium	4.7	2.35	Eddy Current Separation	0.9	6.35	5.715
Copper	7	3.5				
Other Matels	1	0.5				
Glass	5.4	2.7	Heavy Mediam Separation	0.75	8.1	6.075
Rubber	1.1	0.55				
Concret and ceramics	2	1				
Others	7.7	3.85				
Recalculate					Total Material Recovered:	43.19

Figure 5. Material composition data for the refrigerator.

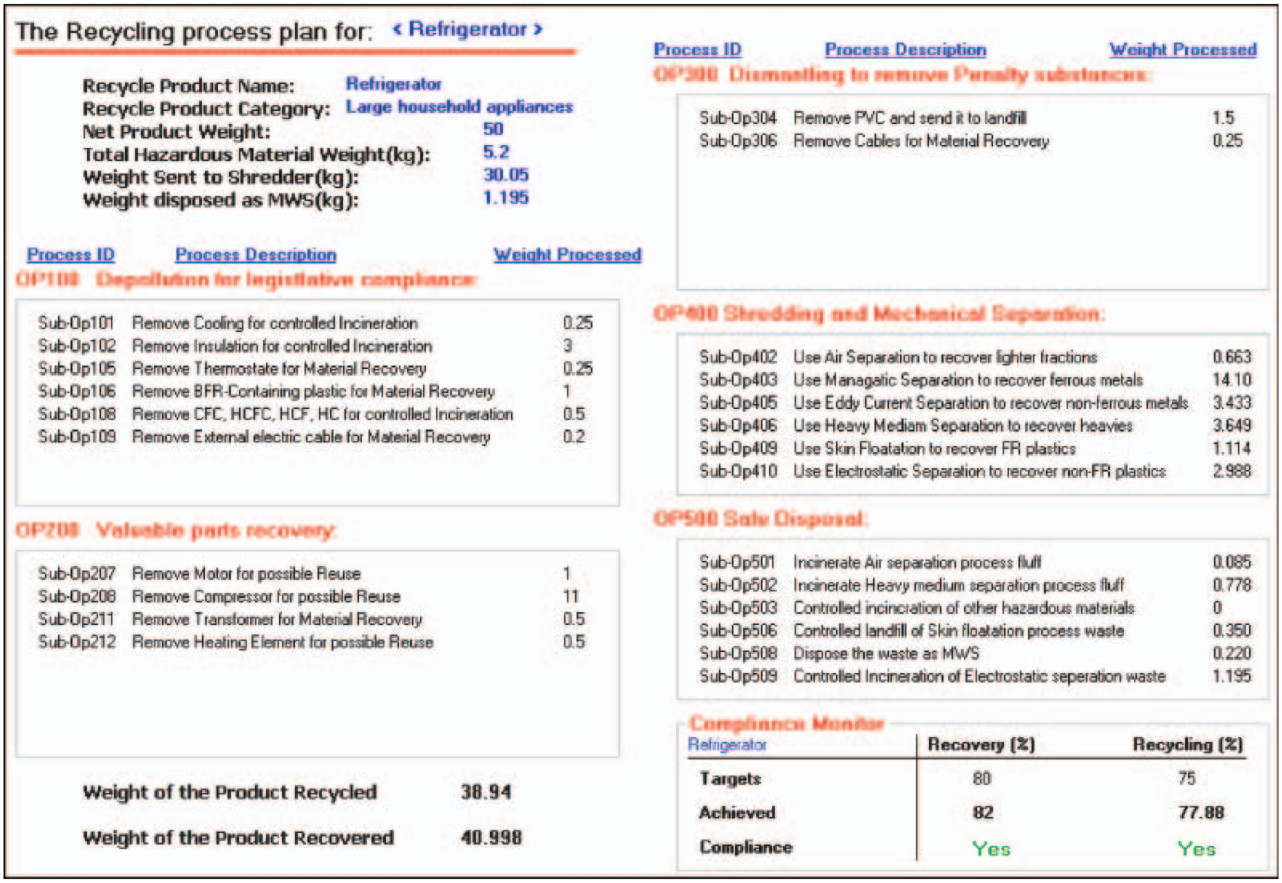


Figure 6. Recycling process plan for the refrigerator.

Similarly, Equations (2) and (4) are used to calculate the economical performance limits (cost/benefit values summarised in Figure 7(b)). It should be noted that negative value for upper economical value 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

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

5.4 *Actual performance of different EoL options for refrigerator*

Based on the EoL destination of each material, an ecological impact value and various EoL costs are assigned to individual materials contained in the refrigerator. The actual performance of the 'Recycling through shredding after depollution' option is summarised in Figure 8. Weights of different materials contained in the refrigerator are calculated using the material composition data in Figure 5. Equations (5) and (6) are used to calculate the actual ecological and economical performance of the refrigerator through shredding option.

Actual ecological performance through shredding

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

Actual economical performance through shredding

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

The recycling process plan contains bespoke recovery and recycling processes for the EoL treatment of the refrigerator. Based on the EoL destination of each material, an ecological impact value and various EoL costs are assigned to individual processes contained in the recycling process plan for the refrigerator. For the recycling of sub-assemblies and components contained in the refrigerator, sensible assumptions about their material composition are made to calculate their ecological and economical impacts. For example, in the case of the material substitution value for external electric cable (−1079 mPt), it is assumed that

(a)

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) Material Substitution (Eli bcs)	Environmental Impact (mPt/Kg) Landfill (Eli wcs)	mi x Eli bcs (mPt)	mi x Eli wcs (mPt)
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

(b)

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) Material Revenue (Cli bcs)	Costs and Benefits (£/Kg) Disposal Cost (Cli wcs)	mi x Cli bcs (£)	mi x 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

Figure 7. Performance limits for the refrigerator. (a) Calculation of ecological performance limits. (b) Calculation of economical performance limits.

the cable contains 70% of copper and 30% polyethylene. Using the individual material substitution values of copper (−1400 mPt) and polyethylene (−330 mPt), the material substitution value for cable is calculated as $0.7\times(-1400)+0.3\times(-330)=-1079$ mPt. A similar technique is used to calculate the costs and benefits involved in the recycling activities for sub-assemblies and components. Equations (5) and (6) are used to calculate the actual ecological and economical performance for the refrigerator through the recycling process plan option. Calculation of the actual performance of the 'Recycling through recycling process plan' option is summarised in Figure 9.

Actual ecological performance through recycling process plan option

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

(a)

Material	Weight (Kg) (mi)	Environmental Impact (mPt/Kg) (Eli ap) Material Substitution	Landfill	Incineration	Process Efficiency (PEi)	Grade (Gi)	mi x Eli ap x PEi x Gi (mPt)
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

(b)

Material	Weight (Kg) (mi)	Costs and Benefits (£/Kg) (Cli ap) Processing Cost	Disposal Cost	Material Revenue	Process Efficiency (PEi)	Grade (Gi)	mi x Cli ap x PEi x Gi (£)
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

Figure 8. Actual performance of recycling through shredding after depollution option. (a) Calculation of actual ecological performance. (b) Calculation of actual economical performance.

Actual economical performance through recycling process plan option

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

5.5 *Comparison of the performances of different EoL options for the refrigerator*

The performances of different EoL options for the refrigerator are presented in Table 1. It is to be noted that by definition the lower performance limit represents the EoL performance of the refrigerator through the land-filling option. Figure 10 evaluates the ecological and economical performance of different EoL options and compares them with the respective performance limits.

5.6 *Generation of the combined ratios for ranking different EoL options*

Finally, the combined Eco^2 performance ratios of different EoL options providing an overview of their ecological and economical performances are calculated. As the environmental concerns and the economical concerns are considered equally important in this paper (the emphasis can be changed by giving different coefficients to ecological and economical performance ratios in Equation (9)), the

(a)

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		
Depollution								
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

(b)

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		
Depollution								
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

Figure 9. Actual performance of recycling through the recycling process plan option. (a) Calculation of actual ecological performance. (b) Calculation of actual economical performance.

combined Eco[2] performance ratio is calculated by taking the 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 EoL options is outlined below.

Table 1. Overall performance of different EoL options.

EoL option	Ecological performance (mPt)	Economical performance (£)
Upper limit of performance (zero landfilling)	−14131.84	−14.58
Recycling through shredding after depollution	−6036.15	3.77
Recycling through recycling process plan	−9660.72	−3.69
Lower limit of performance (100% landfilling)	103.21	12.01

The upper and lower performance limits for the refrigerator are calculated in Section 5.3 and are:

- Upper ecological performance limit $BCS_{ecol} = -14131.84\,\text{mPt}$
- Lower ecological performance limit $WCS_{ecol} = 103.21\,\text{mPt}$
- 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 5.4 and are:

- Actual ecological performance $AP_{ecol} = -6036.15\,\text{mPt}$
- Actual economical performance $AP_{econ} = £3.77$

Equations (7) and (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 (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 the 'recycling process plan option' are calculated in Section 5.4 and are:

- Actual ecological performance $AP_{ecol} = -9660.72\,\text{mPt}$
- Actual economical performance $AP_{econ} = -£3.69$

Equations (7) and (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 (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

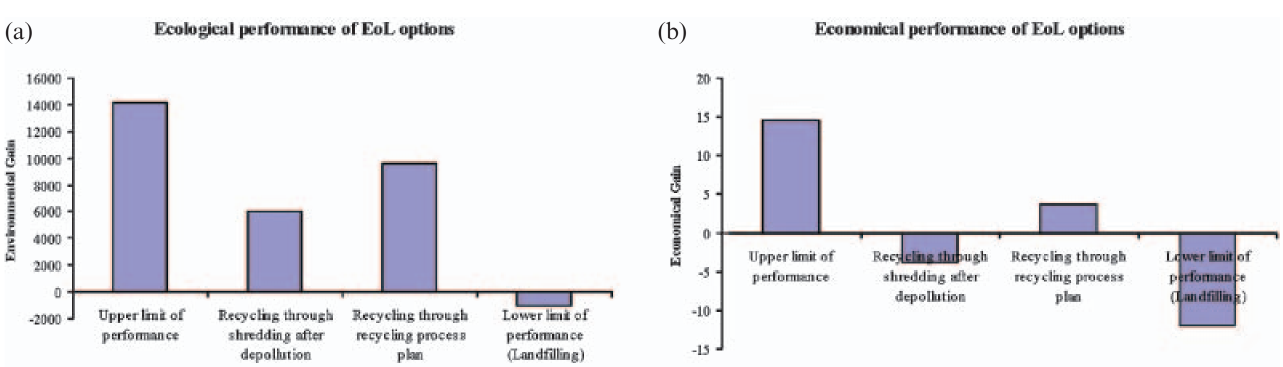


Figure 10. Comparison of performances of different EoL options for the refrigerator. (a) Ecological performance of EoL options. (b) Economical performance of EoL options.

different EoL options for the refrigerator are summarised in Table 2. The 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 4.6 for these calculations). As the higher value of C*E*PR (close to 1) represents a good overall performance of the assessed EoL option, it can be concluded from the results in Table 2 that the overall performance of the EoL option based on the bespoke recycling process plan (C*E*PR = 0.638) is significantly better than the current state-of-the-art practice (shredding after depollution option) (C*E*PR = 0.37). Figure 11 depicts the ranking of different EoL options for the refrigerator in relation to the best and worst case scenario.

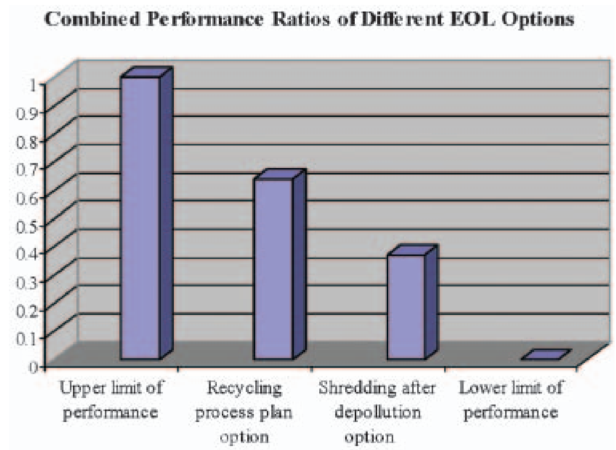


Figure 11. Overall ranking of different EoL options for the refrigerator.

6. Conclusions

The growing amount of WEEE and the wide range of products and materials contained within this waste stream highlight the need for a systematic approach to deal with the complex EoL management of electrical and electronic waste. The authors argue that the current ad hoc approaches to WEEE recycling, which are often based on the capabilities and available resources within the recycling facilities, will not provide long term sustainable solutions for this sector. One of the main problems in the EoL management of WEEE is to identify to what extent products must be disassembled and which EoL option should be applied while minimising the environmental and economical impacts of products' recycling. The systematic assessment methodology presented in this paper provides an integrated approach to identify the ecological and economical impacts associated with different EoL options for WEEE. The parallel consideration of the ecological and economical impacts of different recovery and recycling processes through Eco^2 methodology also provides a simple but effective process to highlight impacts of various EoL options for WEEE in the form of performance scores which are easier to interpret and use than the conventional LCA results. Therefore, it is claimed that the application of the Eco^2 assessment can significantly improve the EoL management of WEEE by supporting the decisions involved in the selection of the most appropriate EoL options for individual products.

One of the fundamental conclusions from this research is that future legislation should contain recovery and recycling targets for individual material streams in WEEE based on their potential EoL ecological and economical impacts as opposed to weight-based recycling targets for different categories of EEE. Finally, the knowledge gained through conducting the Eco^2 assessment could potentially offer valuable support for improvements in the design of new generations of electrical and electronic products.

Table 2. Performance ratios for different EoL options for the refrigerator.

EOL option	**Ecological performance ratio (EPR_{ecol})**	**Economical performance ratio (EPR_{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**

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