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Recycling process planning for the End-of-Life management of waste from electrical and electronic equipment

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ABSTRACT

The ever-increasing amount of waste from electrical and electronic equipment (WEEE) has become a common problem due to the significant environmental and health impacts associated with inappropriate End-of-Life (EoL) management. The current ad hoc applications of WEEE recycling are often based on limited knowledge and cannot cope with the complex range of materials and products in such waste. A knowledge-based approach has been utilised to investigate the realisation of a recycling process planner which aims to determine the most suitable EoL options for WEEE. A number of case studies have been used to show that a 20–30% improvement on economical and environmental performance could be achieved through adoption of such a systematic approach to recycling process planning.

1. Introduction

Technological innovation and shorter product life cycles of electrical and electronic equipment coupled with their rapidly growing applications have resulted in generation of enormous amount of WEEE which is expected to increase further by 3–5% per annum [1]. This has resulted in the introduction of Producer Responsibility (PR) directives for WEEE in the EU, in which manufacturers and importers are made responsible for the take back and recycling of their products [2]. The main objective of such PR directive was to involve the manufacturer in the EoL management of their product. However, the current implementation of this directive has failed to achieve its objective, as many manufacturers have opted to conform to the WEEE directive by moving away from actively fulfilling the requirements themselves, in favour of subcontracting the recovery and recycling of their products through a number of producer compliance schemes. Hence, the burden of WEEE recycling has been placed on an isolated recovery industry with a superficial understanding of the products they are recovering. These recovery facilities are often developed on an ad hoc basis and mainly due to the hidden economic value within the used products. The recovery treatments and recycling activities in these facilities are mainly based on the limited capabilities and available resources without any detailed assessment of the environmental benefits of the recycling activities. However, such recycling facilities are now faced with the challenge to improve their recycling activities and recover a larger proportion of components and materials at a reasonable cost and at the same time to meet the ever-increasing number of legislative requirements [3,4].

The research reported in this paper aims to take advantage of the benefits provided by a knowledge-based process planning approach in manufacturing applications and apply a similar principle to increase the efficiency of recycling activities. The proposed recycling process planner (RPP) utilises a *variant* approach [5], in which the similarities in the features and attributes among a family of products/parts are used to select and modify a predefined 'standard process plan' to generate a bespoke recycling process plan for an electrical/electronic product. A number of case studies have also been presented to highlight the significant improvements in the ecological and economical performances of the WEEE recycling that can be achieved through adoption of the RPP.

2. Recycling process planning framework

The recycling process planning framework consists of four stages, namely a product evaluation, a legislative compliance monitoring, a recycling process planning, and an Ecological and Economical (Eco^2) assessment, as depicted in Fig. 1. In this figure, the information generated and exchanged among various stages is represented by arrows. The product evaluation stage is used to identify appropriate design information required to plan the recovery and recycling processes. This information is also used in the second stage to identify various requirements for legislative compliance. Subsequently, in the third stage a specific set of recovery and recycling processes is generated in the form of a bespoke recycling process plan. Finally, the Eco^2 assessment stage analyses the impacts associated with the EoL processes proposed by the RPP. Due to significant requirements for information and knowledge processing, a Computer Aided *R*ecycling Process Planning (CA*R*PP) system has been developed (see Fig. 2) to assist designers, manufacturers, and recycling facilities in determining

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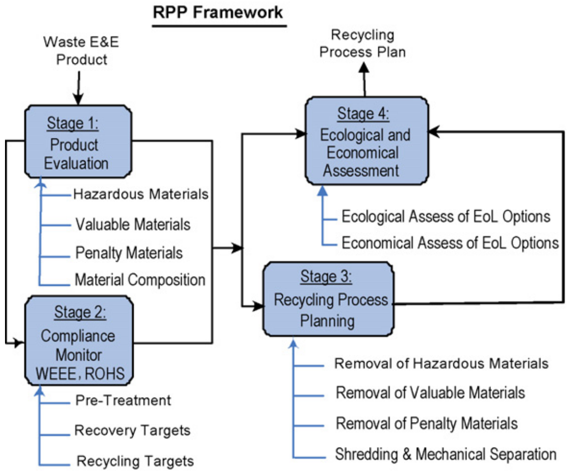

Fig. 1. The four stages in the RPP framework.

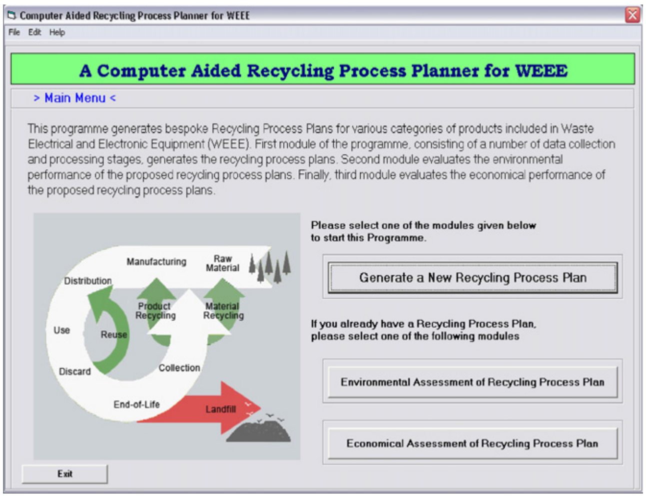

Fig. 2. Computer aided recycling process planner.

the bespoke EoL recycling process plans for individual products in WEEE. At present, any new type of product arriving at a recovery facility is roughly assessed within a workshop to establish how to extract valuable materials and components, with little consideration to environmental impact of recycling activities. It is envisaged that the utilisation of CARPP within such assessment workshop can speed up, introduce consistency, and improve the development of bespoke recycling process plans which can then be stored in an operational database and applied to other similar product families.

At present, in most applications access to initial product design is not available or restricted during the recycling activities, and this absence of "readily available" information is one of the biggest hindrances in adopting effective EoL management for WEEE [6]. The product evaluation stage aims to bridge this information gap by identifying the materials and component mix, hazardous and toxic substances, valuable and reusable parts, contaminating materials, etc. in the product.

The WEEE and Restriction of Hazardous Substances (RoHS) directives [2,7] control the nature and range of recycling processes used for the treatment of WEEE. Hence, the second stage of the RPP framework identifies the legislative requirements related to depollution, recovery and recycling processes for the product under consideration. In the third stage, based on ten product categories introduced by the WEEE directive [2], a number of standard recycling process plans are developed and customised using the information from the product evaluation and legislative compliance monitoring stages to generate bespoke recycling process plans for individual products. This *variant* approach to process planning has been adopted due to the potential for the reuse of the recycling process plans for families of products included in WEEE. Fig. 3a depicts the bespoke recycling process plan for a microwave oven generated using the RPP framework. It is claimed that the utilisation of such a recycling process plan facilitate the adoption of various feasible EoL strategies [8,9] (reuse, refurbishment, material recycling, incineration, and safe disposal) for different components and materials contained in a product to improve the overall performance of WEEE recycling.

In the Eco^2 assessment stage, Eco-indicator 99 methodology [10] and cost–benefit analysis are used to assess the ecological and economical impacts associated with the recovery and recycling processes involved in different EoL options for WEEE. The Eco^2 assessment identifies the composition of main materials like ferrous metals, non-ferrous metals, flame retardant plastics, etc. present in the product. This information is used to identify various feasible EoL options for the disposed product under consideration. Performance limits are then calculated to provide a scale for the evaluation and assessment of the actual ecological and economical performance of different EoL options.

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). Similarly, 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. Table 1 outlines Eqs. (1)–(4) that are used to calculate these upper and lower ecological performance limits (see Fig. 3b), as well as the economical performance limits.

The actual ecological performance (AP_{ecol}) of a specific EoL option of a product is calculated by Eq. (5). Provisions are made for the material degradations and process inefficiencies to be

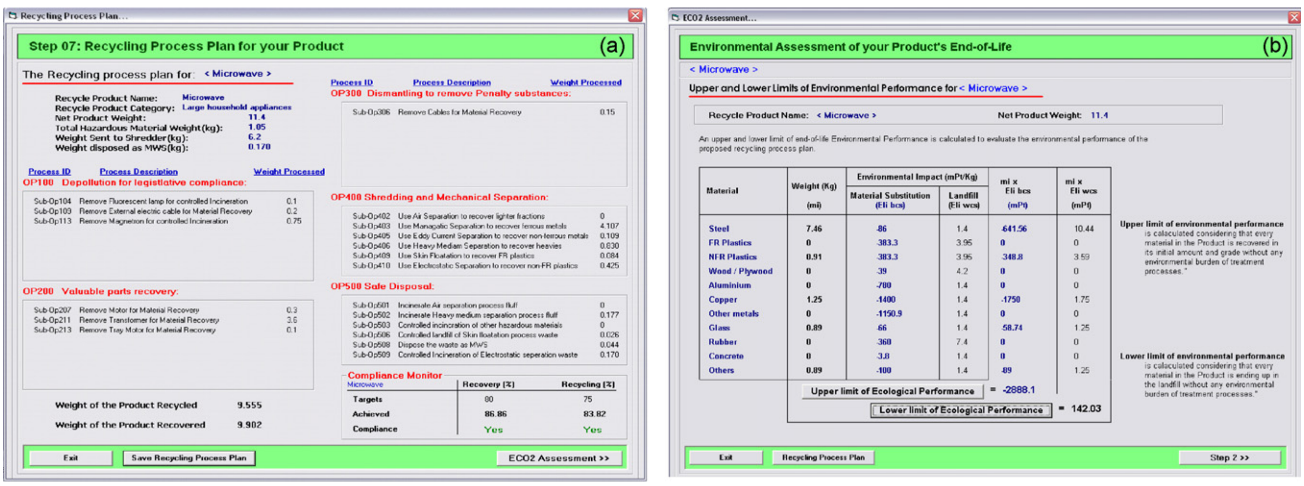

Fig. 3. (a) Bespoke recycling process plan for the microwave oven and (b) Calculation of the ecological performance limits.

Table 1
Equations for calculating Eco^2 performances.

Calculation of the performance limits	
Ecological performance limits	Economical performance limits
$BCS_{ecol} = \sum_{i}^{n}(m_i \times Eli_{BCS})$ (1)	$BCS_{econ} = \sum_{i}^{n}(m_i \times Cli_{BCS})$ (2)
$WCS_{ecol} = \sum_{i}^{n}(m_i \times Eli_{WCS})$ (3)	$WCS_{econ} = \sum_{i}^{n}(m_i \times Cli_{WCS})$ (4)
BCS_{ecol}: upper limit (best case scenario) of ecological performance (mPt); WCS_{ecol}: lower limit (worst case scenario) of ecological performance (mPt); Eli_{BCS} ecological impact of material *i* in the best case scenario (mPt/kg); Eli_{WCS}: ecological impact of material *i* in the worst case scenario (mPt/kg)	BCS_{econ}: upper limit (best case scenario) of economical performance (£); WCS_{econ}: lower limit (worst case scenario) of economical performance (£); Cli_{BCS}: material revenue of material *i* in the best case scenario (£/kg); Cli_{WCS}: material revenue value of material *i* in the worst case scenario (£/kg)
Calculation of the combined ratios for ranking different EoL options	
Ecological performance ratio (EPR_{ecol})	Economical performance ratio (EPR_{econ})
$EPR_{ecol} = \frac{AP_{ecol} - WCS_{ecol}}{BCS_{ecol} - WCS_{ecol}}$ (7)	$EPR_{econ} = \frac{AP_{econ} - WCS_{econ}}{BCS_{econ} - WCS_{econ}}$ (8)
Combined Eco^2 performance ratio = CEPR = $\frac{EPR_{ecol} + EPR_{econ}}{2}$ (9)	

considered while calculating the actual ecological performance associated with different EoL options. A parametric cost–benefit analysis approach is used to calculate the actual economical performance of different EoL options of the product. 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 to define a cost impact for a specific end-of-life option (see Eq. (6)).

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

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

where m_i is the mass of material *i* in the product (kg); PE_i the efficiency of the separation process used for material *i*; Eli_{AP} the ecological impact of material *i* in an EoL route (mPt/kg); Cli_{AP} the cost impact of material *i* in a certain EoL route (£/kg); G_i is the grade in which material *i* is recovered.

Once the actual ecological and economical performances associated with different EoL options for a specific product are calculated, they are evaluated in conjunction with the respective upper and lower performance limits. In this evaluation, the closer the actual performance is to the upper performance limit (representing the best case scenario) the better is the assessed EoL option. However, while evaluating the actual ecological and economical performances of various options separately, the combined impact of the ecological and economical performance is not transparent. In most cases, this will lead to difficulties in decision making as the ecological performance for specific EoL options maybe higher, whereas the economical performance of other options may be better. This highlights the need to develop a combined performance measure to support the selection of most suitable EoL option. Hence, the performance results are combined in the form of 'ecological and economical ratios' to establish the rankings of different EoL options. A data analysis method has been adopted which normalises the ecological and economical performance results and combines them into a 'single ecological and economical performance ratio', referred to as combined Eco^2 performance ratio (CEPR). Table 1 outlines Eqs. (7)–(9) that are used to calculate the normalised ecological performance ratio (EPR_{ecol}), economical performance ratio (EPR_{econ}) and combined Eco^2 performance ratio (CEPR). The CEPR 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).

It should be noted that in this calculation equal importance is given to both the ecological performance and the economical performance but this can be changed by assigning different coefficients to performance ratios. For example in a case where more emphasis needs to be placed on ecological performance due to specific product characteristics, a higher coefficient (e.g. 0.75 for EPR_{ecol} and 0.25 for EPR_{econ}) can be used in Eq. (9).

3. Application of the recycling process planner

Three case studies have been utilised to demonstrate the benefits of RPP approach. These case studies represent products from different categories of WEEE to provide a broad perspective for the evaluation of the RPP approach. The first case study 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 de-pollution requirements and high potential hidden value. The second product is a 'desktop computer' (central processing unit, mouse, screen and keyboard included) which belongs to the 'IT/Telecommunication equipment' category in the WEEE directive. It consists of a variety of materials and components including hazardous substances. Specific pre-treatment requirements have been identified for the screen (cathode ray tube) in the WEEE directive. The recovery and recycling of the computer is complex and more problematic than the microwave oven. In contrast, the third product is an 'electric 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.

The CARPP is used to generate the bespoke recycling process plans for these products and to calculate the ecological and economical performance, as summarised in Table 2. The analysis of ecological and economical impacts of various EoL options for the case study products have shown that the recycling activities based on recycling process plan for all three products provide higher ecological and economical performances and therefore better combined performance ratios when compared with the state-of-art existing recycling practices (i.e. mainly shredding after statutory de-pollution). The improvement in the EoL performances of the case studies resulted by using bespoke recycling process plans is illustrated in Fig. 4.

The analysis of the case study results highlights that 20–30% potential improvements can be obtained through utilisation of RRP approach. Fig. 4 indicates that the improvement in the ecological performance is greatest in the case of a complex product (i.e. desktop computer), whereas the improvements in the economical performance is greatest in the case of a product with high metallic content and low de-pollution requirements (i.e. microware oven). However, in the case of the electric kettle which is a non-metallic (plastic dominated) low value product, the application of RPP has resulted in limited improvement.

Table 2
Comparison of the case studies results.

EoL option		Ecological performance ratio (EPR_{ecol})	Economical performance ratio (EPR_{econ})	Combined Eco^2 performance ratio (CEPR)
Upper limit of performance		1	1	**1**
Microwave oven	Shredding after de-pollution option	0.51	0.34	**0.43**
	Recycling process plan option	0.82	0.58	**0.7**
Desktop computer	Shredding after de-pollution option	0.35	0.3	**0.28**
	Recycling process plan option	0.7	0.4	**0.55**
Electric kettle	Shredding after de-pollution option	0.25	0.2	**0.23**
	Recycling process plan option	0.28	0.25	**0.26**
Lower limit of performance		0	0	**0**

Furthermore, the analysis of the operational breakdown of Eco^2 performance, as depicted in the case of microwave oven in Fig. 5, highlights the greatest potential improvements in ecological performance that could be gained with minimum increase in recycling cost. It is clear from this analysis that the greatest ecological and economical improvements can only be realised through removal of valuable and reusable components. Finally, although the removal of penalty (contaminating) material is currently not commonplace in recycling practices, the Eco^2 performance analysis shows that such decontamination process will significantly improve the subsequent post-fragmentation material recovery, and also result in improvement of economical performance of the recycling activities. Such operational breakdown analysis could be used to support the strategic decisions related to the capital investment for improvement in recycling facilities.

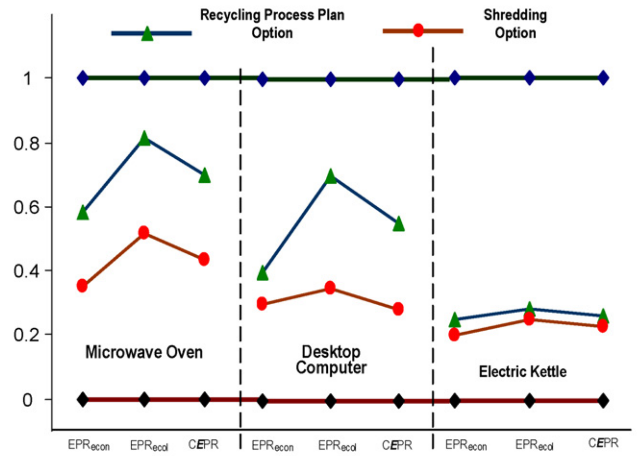

Fig. 4. Comparison of the case studies results.

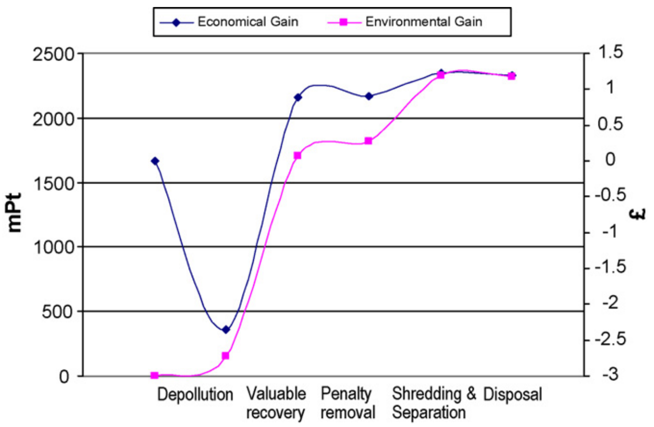

Fig. 5. Operational breakdown of ecological and economical gain for microwave oven.

4. Conclusions

The proposed recycling process planning approach aims to take advantage of the significant benefits provided by process planning in manufacturing applications and apply a similar principle to increase the efficiency of recycling activities. The RPP framework determines the most suitable trade-offs between ecological and economical variables and includes simultaneous consideration of the macro- and micro-level EoL planning to identify an appropriate sequence of eco-efficient recycling processes for individual products in WEEE.

The reduction of the hidden value in electrical and electronic products is impacting the economics of WEEE recycling. This clearly highlights 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. The current recycling practices of meeting the recovery and recycling obligations at a marginal cost is very much dependant on the high scrap metal prices. 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, and hence it is argued that the adoption of proposed RPP approach to planning of recycling activities for WEEE could be of paramount importance in ensuring the long term sustainability of WEEE recycling. Finally, it is envisaged that CARPP would enable manufactures as well as recyclers to determine the EoL cost associated with particular product upfront leading to better cost negotiations with their product recovery agents which would in turn encourage manufacturers to improve the design of their products with EoL considerations.

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