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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].

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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

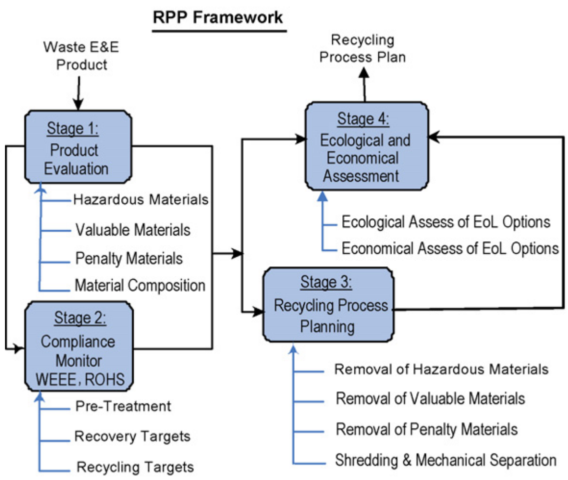

Fig. 1. The four stages in the RPP framework.

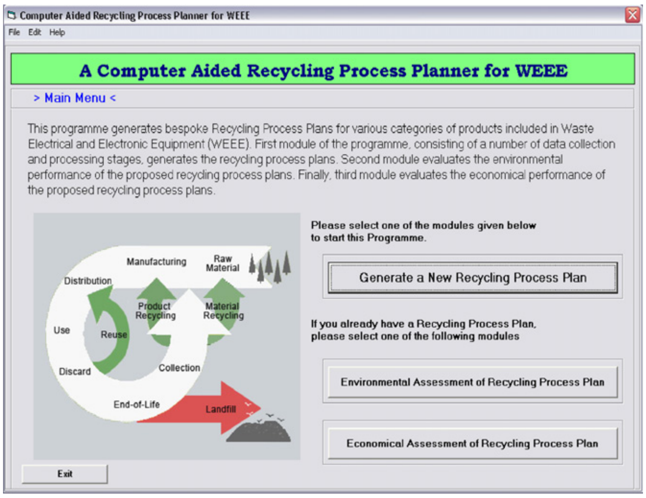

Fig. 2. Computer aided recycling process planner.

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

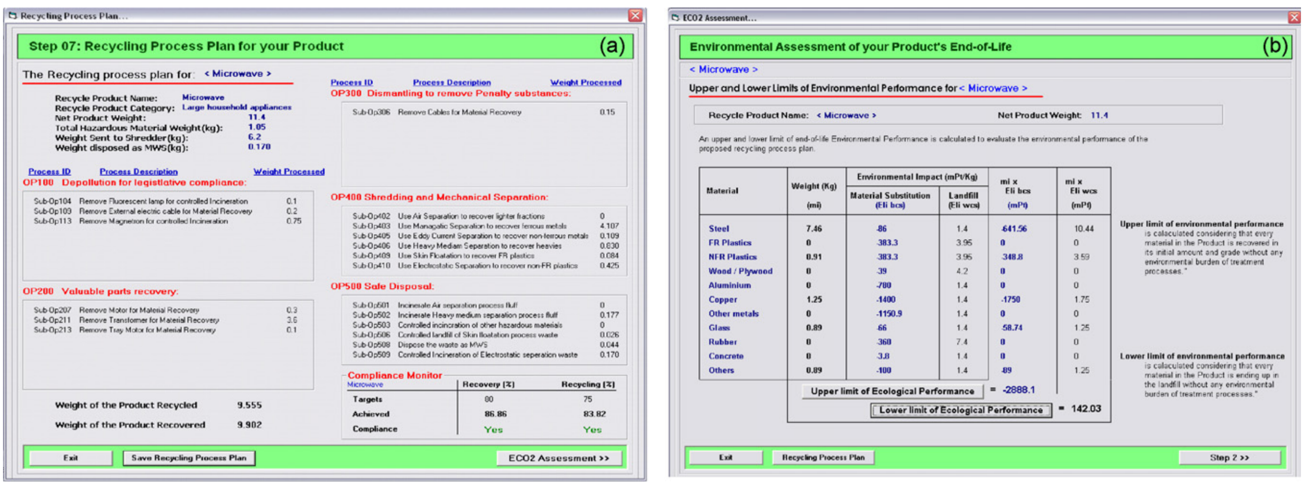

Fig. 3. (a) Bespoke recycling process plan for the microwave oven and (b) Calculation of the ecological performance limits.