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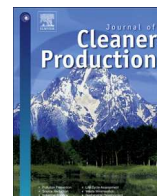
Towards cleaner production: a roadmap for predicting product end-of-life costs at early design concept

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ABSTRACT

The primary objective of the research was to investigate how disposal costs were being incurred in the domain of defence electronic systems by the Original Equipment Manufacturer (OEM) and subsequently to ascertain a novel approach to prediction of their end-of-life (EOL) costs. It is intended that the OEM could utilise this method as part of a full lifecycle cost analysis at the conceptual design stage. The cost model would also serve as a useful guide to aid decision making at the conceptual design stage, so that it may lead to the design of a more sustainable product in terms of recycling, refurbishment or remanufacture with the consideration of financial impact. The novelty of this research is that it identifies the significance of disposal costs from the viewpoint of the OEM and provides a generic basis for evaluation of all the major EOL defence electronic systems. A roadmap has been proposed and developed to facilitate the prediction of disposal costs and this will be used to determine a satisfactory solution of whether the EOL parts of a defence electronic system are viable to be remanufactured, refurbished or recycled from an early stage of a design concept. A selected defence electronic system is used as a case study. Based on the findings, the proposed method offers a manageable and realistic solution so that the OEM can estimate the cost of potential EOL recovery processes at the concept design stage.

1. Introduction

"Cleaner Production" is one of the strategies to improve a product's end-of-life (EOL) by waste reduction, recycling and reuses (Khalili et al., 2014). In the last decade, traditional options for EOL processing of Waste Electrical and Electronic Equipment (WEEE) such as landfill and incineration have prevailed (Tojo et al., 2011). These options are a concern due to the depletion of raw materials, pollution, and overflowing waste sites (Gungor and Gupta, 1999). It is well known that Japan has a proactive attitude to electronics recycling (Goosey, 2009). With the 'Home Appliance Recycling Law'

in 2001, they were one of the first countries to put producer responsibility of Electrical and Electronic Equipment (EEE) into law. The European Union (EU) followed up by publishing several directives to restrict the quantity and nature of waste arriving at landfills (Ravi, 2012). The WEEE directive, for example, requires member states to recycle and recover 50—80% of household WEEE and holds the producers of EEE financially responsible for this. Despite all these efforts, the current waste recovery rate in the manufacturing sector in Europe is far below the EU's target at about 16% (Fikru, 2014).

In addition to legislative reasons, original equipment manufacturers (OEMs) have a higher incentive to design with EOL in mind due to the opportunity costs attached to changing consumer perspectives. This has led to an increasing adoption of design for environment and design for remanufacturing to add value by marketing environmentally friendly, or green products (Hatcher et al., 2011). Complimenting this is the electronic product environmental assessment tool, which provides a way to compare

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Abbreviations

B2B	business-to-business
B2C	business-to-consumer
BOM	bill of materials
CAD	computer aided design
CE	cost element
EEE	electrical and electronic equipment
EOL	end-of-life
EPR	extended producer responsibility
LCC	lifecycle cost
MFD	multi-functional display
OEM	original equipment manufacturer
pdf	probability density function
RoHS	restriction of hazardous substances
StEP	solving the e-waste problem
TPO	third party organisation
WEEE	waste electrical and electronic equipment

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electronic products based on environmental performance through eco-labelling (Katz et al., 2005). In competitive markets this puts pressure on OEMs to proactively take-back and recover their products at EOL.

Confronted with these issues, OEMs are reacting to the need to implement 'lifecycle thinking' (Go et al., 2011). According to Cheung et al. (2009), a product's lifecycle is defined as the "whole life of the product from concept to end-of-life". It follows that, addressing the entire product lifecycle requires the need for adopting an approach to lifecycle cost (LCC) analysis. LCC analysis usually models a product's life, from its design, manufacture, assembly, distribution and use. This approach, however, often gives little thought about EOL, since every product has to be dealt with as EOL once it reaches this stage. If a system was developed to predict the cost of its EOL value, it may lead to designs more suitable for products' recycling and reuse, which may lead to greater profit margins and also a more sustainable product to reduce environmental footprints (Cucek et al., 2012). Therefore, many manufacturers are aware that sustainable product development is an important issue (Lee et al., 2014). Rather than perform the recovery process at the EOL of an electronic product, the proposed method discussed in this paper will be used to predict the end-of-life in terms of costs. These costs can then be used to assist the designers in making design decisions at the conceptual design stage. In particular, the method can be used to predict viability for remanufacturing, recycling and refurbishment as opposed to simply sending to landfill.

2. Literature review of end-of-life cost modelling in electronic products

According to Rahimifard and Clegg (2007), there has been a significant growth of research, on an international scale, to develop better management of sustainable production and products. Particular focus has been devoted to the in-use and disposal, or EOL stages of the product lifecycle as these often carry the greatest environmental impact (Ostlin et al., 2009) and environmental performance (Fikru, 2014). Such 'lifecycle thinking' has led to an unavoidable attention to the importance of design (Candido et al., 2011).

Zuidwijk and Krikke (2008) developed an approach utilising product information from a disassembly bill-of-materials (BOM) to improve product recovery at the design stage. This approach also considered the economic value of a product recovery option. Gonzalez and Adenso-diaz (2005) provide BOM based evaluation that can establish the most suitable EOL options and disassembly sequence simultaneously. The detailed bottom up approach directly calculates recycling, reuse, disassembly and disposal costs for every subassembly and component. This information can be used to inform for design trade-offs between environmental and economical aims. The approach incorporates a scatter search algorithm (Laguna, 2002) to establish disassembly sequence at any level of a products' assembly structure. The information analysed is sourced from the product's entire BOM, Computer-Aided Design (CAD) model and economic/technical data library. Economic and technical data include average joint breaking times, recycling and disposal rates. This approach may be valuable to optimise the design of products where the intention is to reclaim value, for example, by clustering components of a certain material type to reduce disassembly depth. However, the concept is fairly inflexible in that it assumes that the OEM wishes to demanufacture the entire product at EOL. Whereas, for example, an OEM may expect to only address certain parts, so that the product may be returned to a certain specification, such as for refurbishment. Furthermore, these techniques require a complete BOM and product CAD model which may not be available at the concept design stage.

Most recently, Lee et al. (2014) proposed a 'design for end-of-life' methodology. This approach captures; represents and analyses the knowledge from EOL stages of a product so that designers can use the information to make decisions on design alternatives to optimise a product's EOL performance based on cost of recovery, cost of energy and potential emissions from the recovery processes. After studying Lee's approach, the framework would require a large amount of information such as material toxicity, biodegradability, degree of component or module wear etc. The approach is more applicable to the detailed design stage than preliminary design. Furthermore, the availability and accessibility of the information or knowledge relevant to a product is very important, without these, designers would not be able to analysis the EOL options. Fukushige et al. (2012), proposed a method for lifecycle scenario design for product EOL strategy at an early stage of design. However, the cost estimation of recovery was implemented as a bottom-up approach whereby cost is estimated via process breakdown and summation of detailed cost variables. Zussman et al. (1994) describe a methodology to identify an optimal EOL strategy in design for EOL products. The approach investigates various EOL processes for their cost and value, and incorporates probability density functions (pdf) into cost equations where the EOL option of 'reuse' employs a pdf to model the value of a reusable component in terms of component to product life time ratio. If the ratio is below 2, the component is assumed to have little value for repair and reuse as it would not last another full lifecycle. If it is above 2, its value increases sharply. The pdf is used to determine the most probable ratio, and therefore the most probable value for reuse. Future scenarios are also accounted for in this model e.g. rises in material value. However, as with the study by Gonzalez and Adenso-diaz (2005), the optimal EOL path for every single component is calculated. Though this may yield an accurate result, management of a large amount of information and time consuming calculations are the reasons why an OEM may not decide to adopt the technique.

Some modelling approaches rely less on detailed analysis to estimate cost. Peeters and Dewulf (2012) proposed a design for an EOL method. In their approach they discuss how the method could be used to assist designers to take into account different EOL options including economic cost reduction in the early stages of the design process. Their proposed approach of EOL treatments of WEEE is simplistic, so that it should use less information to predict EOL options in early design. However, there is a lack of evidence

about cost elements in the approach. Zhou et al. (1999) developed a multi-lifecycle product recovery model based on a time varying cost concept that considered product and part lifetimes. This accounts for the fact that certain product parts are used for longer periods than the product. The study adopted the 'recovery problem' (Navin-Chandra, 1994) to find the optimum recovery process. Furthermore, Zhou et al. (1999) focused on the effect of product condition on the cost to reconditioning (refurbishment). The cost required to recondition an electronic product depends on product condition and obeys an exponential distribution in a population of a number of products. The authors applied this model on three major subassemblies within a computer monitor but omitted the separate issue of factors and cost related to disassembly.

Bakar and Rahimifard (2008) present a framework for generating process plans for recycling. In determining the process plans, an economic and environmental cost assessment was made using parametric data. Before choosing the most appropriate plan, the product was evaluated with regard to the WEEE and RoHS (Restriction of Hazardous Substances) directives to determine whether the plan was environmentally suitable to implement. While this approach may evaluate the cost of recycling processes, it is only proposed for use by recovery facilities. A facility using it will typically apply it to collective waste streams of product category to increase recycling efficiency and facilitate WEEE compliance. Therefore the framework is of no interest to the OEM.

Many EOL cost models have adopted a systems approach. For example, Fan et al. (2013) developed a method of evaluating the disassembly and recycling cost of a notebook at its EOL stage. The aim of this research was to support decision making of how such information could be applied into eco-design and the re-design process to enhance recycling efficiency. Bohr (2007) modelled the economic and environmental performance of EOL treatments with a broader approach, taking into account entire recovery/disposal facilities or systems operating in a particular operational or geographical context. In Dahmus's research (Dahmus et al., 2008) factors such as population distribution and participation are incorporated in a model that recognises three main functions in a recovery system: (i) collection, (ii) processing and (iii) system management. The inputs to these functions are described and include various cost items such as transportation, overheads, labour, equipment capital and administration fees. These models are too encompassing and do not analyse inbuilt costs arising from the design choices for a single product.

There are many different descriptions and understandings in state-of-the-art reviews of EOL process options in EEE (Ilgin and Gupta, 2010). Many studies of EOL cost models use a detailed approach, examining products at component level (Fan et al., 2013). However, there is no evidence of an effective component level approach that is flexible enough to work with, given the limited information available at the concept design stage. In order to develop a generic costing approach for these options it is critical that a universally accepted generic definition is examined. It was decided that the only appropriate definitions are the ones provided by StEP (2009) and BS 8887-2:2009 (2009). However, in the case of recycling, there are several different approaches, each containing different sub-processes and, therefore, different cost categories. Thus, recycling goes beyond the generic definition supplied by BS 8887-2 and considers only the recycling method of 'equipment dismantling' described by Kellner (2009). A component level approach was deemed necessary but not one that analysed every last component in detail.

As a result of the literature review, this paper describes an alternative approach, thus only data on cost sensitive components and their *approximate* position in the product structure is required. In order to develop this approach, this paper discusses a generic

method of estimating EOL costs at the design stage of EEE. In addition, this research has also carried out an industrial survey which is discussed in the following section. Therefore, the layout of this paper is as follows: Section 3 describes an industrial survey on EOL issues in the EEE industry. Section 4 discusses the methodology and implementation issues. Section 5 describes a case study and data analysis and, finally, the conclusion and future work is presented.

3. Industrial treatment on end-of-life electronic products

3.1. Industrial research

Prior to the industrial survey, an industrial research exercise was conducted involving interviews with various WEEE stakeholders in the UK to discuss the issues of EOL processes and the effect of the WEEE directive. Most interviews were conducted over the telephone. The participants were a WEEE regulator, a WEEE treatment facility, a WEEE compliance scheme, a distributor of EEE, an IT asset recovery business, a reuse/remanufacturing consultancy, an academic researcher in remanufacturing and an industrial director of an electronics manufacturing research centre. The discussion and findings of this industrial research are summarised as follows:

3.1.1. Industrial director of an electronics manufacturing research centre

"The WEEE directive is a convoluted path to producer responsibility and has so far proven ineffective in reducing land-filled WEEE in the EU. Japan is the only country to fully commit to an individual producer responsibilities approach in WEEE recycling. EOL products are treated as valuable resources in Japan, as opposed to unwanted waste in the UK and US. OEMs have closer business relationships with recyclers in Japan. One effect of this is, for example, that design for disassembly is a generic requirement at the Japanese electronics giant, Sony. Designers themselves are obligated to disassemble the products they design. Regarding OEMs in the EU, this kind of approach is only practised by a minority of informed, enlightened and proactive companies. However there is a trend towards this kind of thinking as effective producer responsibility is the ultimate aim of the WEEE directive and legislation may well adapt to ensure this in the future".

3.1.2. Academic researcher in remanufacturing

"The OEM can remanufacture its products in two ways: (i) by Original equipment remanufacturer or (ii) by outsourcing operations to a contract remanufacturer. The third ineffective form of remanufacturing organisation is the individual remanufacturer. This type generally has either an absent or negative relationship with the OEM. Individual remanufacturing is not as effective because information and spare parts are not provided by the OEM and, in some cases, intellectual property rights can be intruded upon. Compared with repair and refurbishment, remanufacture may not be the most environmentally favourable approach since it requires the use of more resources to meet higher quality specifications. It is, however, considered the most sustainable EOL process. This is because it satisfies all the three pillars of sustainability: environment, society, and economy. Remanufacture is recognised by the UK's WEEE regulations as a form of reuse although it is not referred to as legislation due to a lack of understanding of its definition in industry. However, the reuse subgroup of the WEEE advisory board is looking into ways of helping the UK regulations to facilitate the adoption of remanufacture by OEMs".

3.1.3. Consultancy firm for reuse and remanufacturing

"The main purpose of the WEEE directive was to reduce waste at landfills. In attaining this goal, environmental benefits of reuse and

remanufacture over recycling have had little priority. Despite reuse being encouraged in the UK's WEEE regulations as a priority over recycling, there have been no incentives provided by legislation to facilitate this. The emphasis on recycling may actually be having a negative effect on remanufacturing".

3.1.4. IT asset recovery firm

"The WEEE directive is heavily focused on B2C WEEE, with less incentive provided for OEMs of B2B EEE to increase recycling rates. Indeed recycling and recovery targets only cover B2C WEEE. There is currently no real incentive provided by the WEEE directive for OEMs to design for disassembly, reuse, remanufacture and recycling. Furthermore, a lot of used IT equipment is exported under the guise of reuse, when in reality this may not occur and hazardous waste is not properly treated. A specification for reuse of EEE is being developed by the reuse task group of the WEEE advisory board. Among other aims, this will place a minimum standard for the quality and safety of repaired and refurbished WEEE or EEE and prevent products labelled as reuse, but unfit to be reused abroad, from being exported".

To strength the findings of the above comments made by industrialists, an industrial survey has also been conducted.

3.2. The industrial survey

A survey was conducted to determine various aspects of EOL costs to OEMs in the UK EEE industry. The primary aim was to identify (1) the level of participation; (2) degree of attention given and (3) reasons behind EOL cost estimation. This was helpful in identifying some of the characteristics of a cost estimating approach that are appropriate to the needs of the OEM.

An online questionnaire was prepared and over 100 companies within the EEE industry were contacted. This allowed information to be collated automatically and participants to take part more easily by simply clicking a link in the email and answering the user-friendly formatted questions.

About half of the targeted companies were contacted by telephone prior to emailing the questionnaire to ensure the emailed covering letter was promptly received by the relevant personnel. In a minority of cases, the relevant personnel were spoken to directly. Various companies operating in the UK were chosen such that a range of WEEE categories were covered. Since manufacturers of Business-to-Business (B2B) and Business-to-Customer (B2C) EEE are under different legislative pressures, both were represented evenly. Top management and cost estimating engineers were targeted as it was suggested that these were the most likely candidates for the questionnaire. The populations of companies targeted were mainly selected through the following directories:

- Applegate Directory Ltd. (www.applegate.co.uk)
- Europages (www.europages.co.uk)

The questionnaire consists of 21 questions (see Appendix), designed to be answered within only 10–20 min to maximise the rate of reply. The questions required a mix of qualitative and quantitative answers, and four main areas were covered:

1. Company background (questions 1–5)
2. End-of-life cost estimation in lifecycle cost analysis (questions 6–12)
3. Design for end-of-life and product take-back (questions 13–16)
4. Influence of the WEEE directive (questions 17–21)

3.3. Industrial survey results and discussions

Of the companies contacted, 14 of them took part in the questionnaire. For company background, there was a fairly even population of generic B2B and B2C companies. In total 6 of the 10 WEEE categories were covered, a majority of these companies described themselves as design and manufacturing. Companies were asked to rank the stages of their product lifecycle by cost. Fig. 1(a) shows that the EOL stage is regarded as the least costly. In addition to this, all participants claimed that the EOL stage accounts for below 7% of the total LCC of their products. Nearly half of the participants claimed this figure to be below 5%.

Fig. 1(b) indicates that about a third of companies apply lifecycle costing and a third consider EOL costs in their product cost estimation. Yet, over 90% of companies do not use software packages to facilitate cost estimation. Only one company claimed to use software package and this software was not used to predict EOL costs. Those that did not use software packages gave the following explanations:

- They are not likely to improve on spread-sheeting;
- They are not worth the investment;
- They are inflexible.

As suggested in Fig. 2(a), most companies do not consider EOL costs in design. It was discovered that a minority of companies reclaim value from their EOL products and take them back for recycling or reuse operations (either in-house or via a contracted facility). All the companies that implemented this were B2B. Of these
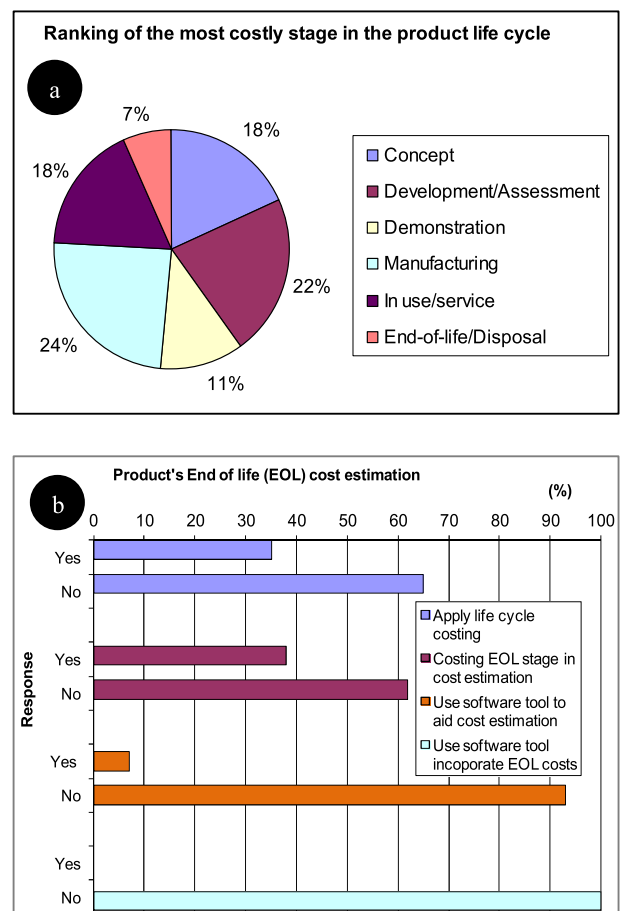

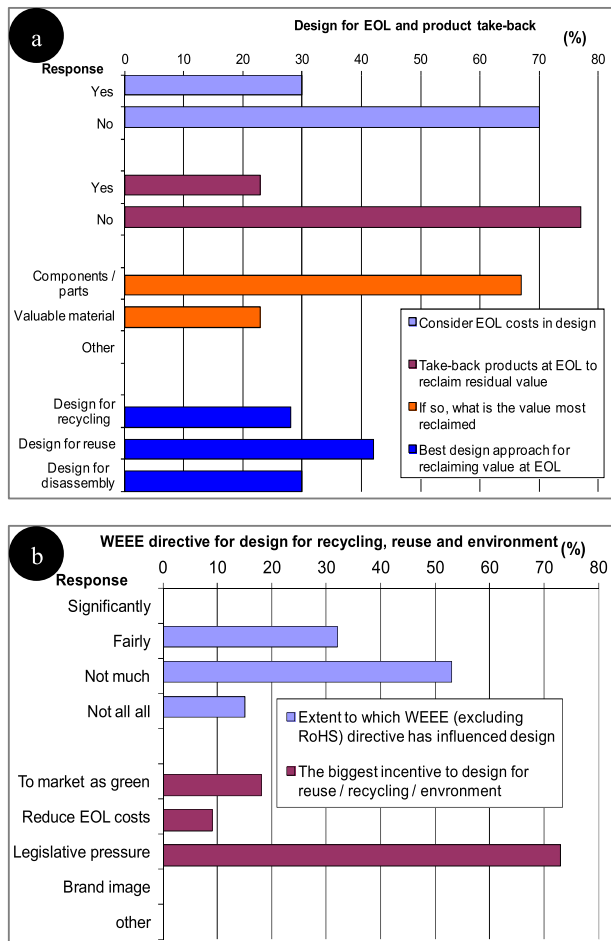**Fig. 1.** (a) Product lifecycle; (b) EOL cost estimation.

Fig. 2. (a) Product take-back; (b) WEEE directive for design.

value in their EOL products. Of the companies that did take-back products, extracting the residual value in them was more commonly achieved via component or part reuse. Indeed most of the companies would consider design for reuse, of components or products, before the other design for EOL approaches. No one company regarded design for disassembly as the least important of the three design approaches, and this emphasises the importance of disassembly in either reuse or recycling.

The WEEE directive was not considered by participants as an effective legislative tool in spurring design for recycling, reuse or the environment. Instead, design for reuse and recycling was heavily focused on maximising profit from products worth taking back for their residual value. Due to these reasons, a new approach for estimating costs of EOL at the design stage is proposed and this is discussed in the following section.

4. Method and principles of estimating EOL costs at the concept design stage

4.1. Cost estimating approach

As identified in the literature and the industrial survey, there are many options and needs for processing EEE at EOL. The method presented in this section is generic so that it can be applied to all major EOL process options. Thus it is applicable to all EEE in general and not a specific category or type of product.

4.2. Cost categories

Cost categories are linked to the activities that make up the EOL process being modelled. In general, preparation for reuse (e.g. repair, refurbish and remanufacture) includes the following process activities (Millet, 2011):

(i) Disassembly;
(ii) Cleaning (including data erasure);
(iii) Inspection;
(iv) Component exchange, retrieval, or reprocessing (reprocessing may be mechanical e.g. manufacturing operations or electronic e.g. surface mounted devices);
(v) Assembly, including recombination of parts from different cores;
(vi) Testing.

At the next level down, cost categories are measurable resources required to complete the above sub-processes and can be divided into fixed and variable costs. The main resources have been identified as:

(i) *Labour*: to carry out all manual tasks e.g. disassembly, cleaning, etc (variable);
(ii) *Replacement components*: required where used components are not economically viable to make reusable given the required specification (variable);
(iii) *Consumables*: lubrication and cleaning solutions (variable);
(iv) *Overheads*: equipment, energy, etc (fixed).

4.3. Cost elements

Using a cost element concept, cost categories can be linked to the physical make-up of the product. As shown in the example in Fig. 3(a), the following three dimensions are used (BS EN 60300-3-3:2004 (2004)):

• product breakdown into lower indenture levels;
• lifecycle phase when modelled activity occurs;

companies, all of them consider EOL costs in design and most take-back their products to reuse components or parts. Moreover, of the main design approaches to tackle EOL costs and maximise profits, design for reuse was considered most helpful in achieving this.

Fig. 2(b) illustrates the effect of the WEEE directive on product design and incentives for greener design. Most companies admitted that the WEEE directive had not influenced them in product design. In explaining this, a B2B company stated that EOL disposal costs are measured by the mass of the product, while a B2C company noted that they paid EOL costs to the disposal company by their proportion of market share. Despite the ineffectiveness of the WEEE regulations at driving greener design, the vast majority of participants acknowledged that where legislative pressure exists, it can provide a better incentive to design for recycling, reuse and the environment. The opportunity to market a product as green, as with legislative pressure, was considered a bigger incentive to practice EOL cost reduction in design.

In summary, EOL costs of EEE are relatively insignificant to the OEM. Most of the population regarded EOL costs as the least significant in all the lifecycle stages, contributing to no more than 5% of the total lifecycle cost. It seemed that companies generally regarded it as an unnecessary expense. Where software is used, it does not account for the EOL stage. Thus, all the companies that estimate EOL costs do so without the use of cost estimation software, and if employing spreadsheets would need to create their own EOL estimation procedure.

In general, companies did not take part in design for EOL cost estimation unless they considered there to be significant residual

- cost category.

The steps that make up preparation for reuse are applied to the product at different levels. This is depicted by cost elements in Fig. 3(b).

4.3.1. Product-assembly level cost elements

The cost elements at these levels are dominated by disassembly and assembly. Disassembly is a common precondition for recycling or reuse of any component or subassembly within a product (Ardente et al., 2011). Disassembly is manually performed and incurs high costs (Kellner, 2009). The extent to which a product requires disassembly, and subsequent reassembly, so that components of interest are separated is the disassembly depth.

Disassembly cost is commonly considered proportional to disassembly time, where the constant of proportionality is the labour rate (Gonzalez and Adenso-diaz, 2005). Disassembly time depends on disassembly depth which can vary depending on the EOL options. To account for this, a simple disassembly depth factor example is presented on determining a disassembly depth at an assembly level. The factor represents the disassembly depth necessary to reach targeted components or parts. In the case of remanufacture the product is completely disassembled (Pigosso et al., 2010) thus the factor is 1. The disassembly factor (f) is calculated as follows (Zhou et al., 1999):

$$f = \frac{\text{number of assemblies to disassemble}}{\text{total number of assemblies}} \qquad (1)$$

An assembly will require disassembling if it satisfies either or both of the following conditions:

(i) Contains one or more target components;
(ii) Contains lower level assemblies that contain target components.

The assemblies to disassemble can be determined manually by filtering the initial BOM (or, perhaps, pseudo BOM) for the target components, identifying the assembly information for each target component, and visually analysing the assembly structure by counting the assemblies satisfying the above conditions. Fig. 4 illustrates the assembly structure of a hypothetical product containing target components.

The disassembly depth factor for the example in Fig. 4 is:

$$f = 9/15 = 0.6$$

Assumptions and details:

(i) each assembly takes the same time to disassemble (mean);
(ii) disassembly separates an assembly into its constituent components and lower level assemblies;
(iii) the time to separate one or more target components from an assembly is equal to the time to disassemble the assembly;
(iv) if an entire assembly is targeted, the model treats it as a component.

4.3.2. Component level cost elements

As shown in Fig. 4, the costs incurred are typically inspection, cleaning, and component replacement, retrieval and reprocessing/
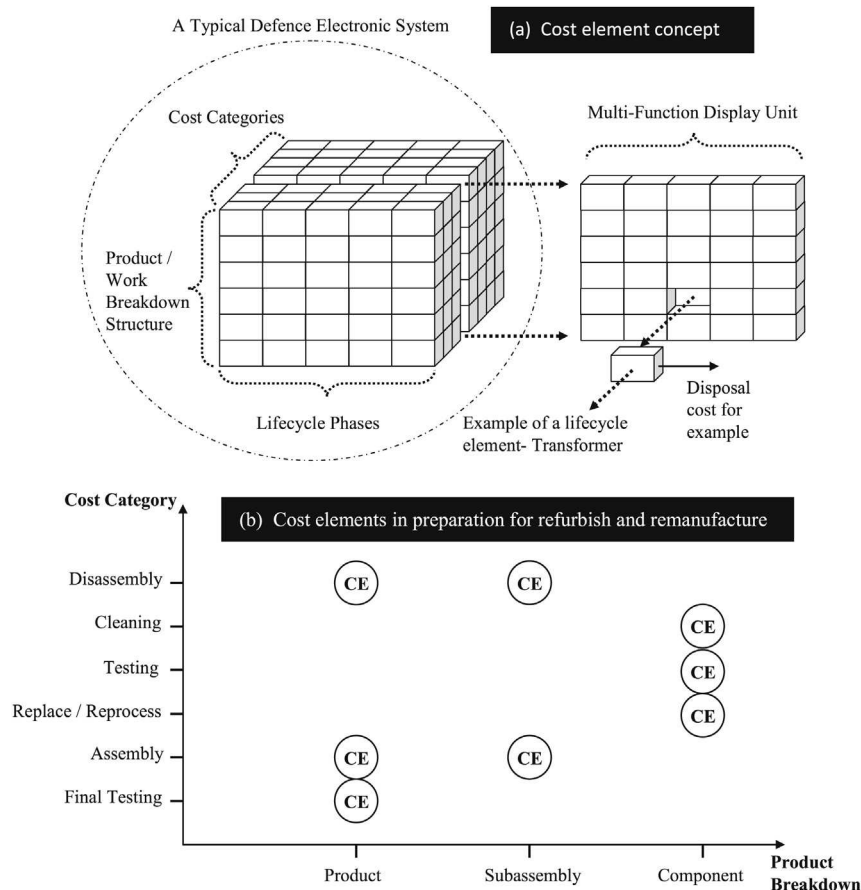

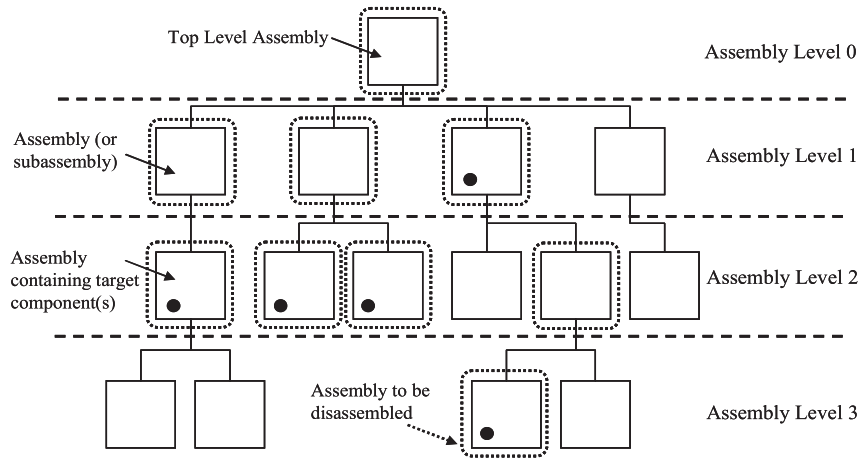Fig. 3. Cost categories and elements.

Fig. 4. Assembly layout of hypothetical electronic product.

rework. As one would expect, these costs vary greatly with the component of interest. Depending on the nature of the component, these costs should be estimated accordingly by the OEM. However, as emphasised by Zhou et al. (1999), a common relationship between these costs and the component of interest is component condition. Therefore, this can be modelled to aid cost estimation per component.

4.4. Roadmap of EOL options at design concepts

EOL options are identified from the viewpoint of the OEM in Fig. 5. An OEM can either implement the take-back and processing of its own EOL products or allow for a non-own-branded TPO to arrange this. With the former, it is assumed that the OEM will have key components of interest in mind. In the case of refurbishment and remanufacture these components are addressed to ensure that the reused product meets a given specification. In the case of recycling, the components of interest are those that have significant inherent value in their material or reuse respectively. When left to a non-own-branded TPO, the OEM has no interest in the EOL product and simply pays the necessary fee for obligatory treatment, recovery and safe disposal. Non-reusable or non-recyclable materials and components will eventually end up in the collective waste

Fig. 5. Roadmap for EOL EEE from the viewpoint of the OEM.

management sphere and be disposed of. In this proposed roadmap, the refurbishment option has taken into account both repair and replacement costs, which are described in Section 4.5.1. Cannibalisation is another option that the proposed roadmap does not consider, this is due to the fact that cannibalisation is only applicable for non-reusable product and hence this will simply be taken into account by the recycling option. Additionally from an early design concept perspective, all components and parts will be considered at EOL.

4.5. Cost equations

A cost equation for each of the three options is presented in this section. The majority are distinguished based on current global definitions.

4.5.1. Refurbishment

According to Zhou et al. (1999) electronic product failure rate follows an exponential distribution. It can be inferred from the British Standard BS 8887-2:2009 that refurbishment addresses major components that are not expected to meet a certain specification at product EOL. Regardless of whether the components have failed, they will be targeted for refurbishment. The likely condition of a target component at the time of expected product EOL can be concluded from failure rate data. If the target component is in good condition at product EOL then a relatively minor refurbishing cost would be incurred e.g. cleaning. In contrast, a failed target component will incur higher refurbishing costs such as repair, replacement, etc. The likely cost to refurbish, according to component failure/degradation rate data, is estimated to be somewhere between these two extremes. For refurbishment cost, the whole expense to refurbish the retired parts to new parts is given by Zhou et al. (1999):

$$C_{\text{refurbish}} = \sum_{i=1}^{k} \left\{ C_{\text{good}} \cdot e^{-\lambda \cdot t} + C_{\text{failure}} \cdot \left(1 - e^{-\lambda \cdot t} \right) \right\}$$
$$+ f \cdot L \cdot (T_{\text{d}} + T_{\text{a}}) \tag{2}$$

where

- i = target component
- k = number of target components
- C_{good} = cost of reconditioning a used part when it is recoverable
- C_{failure} = cost of reconditioning a used part when it has failed
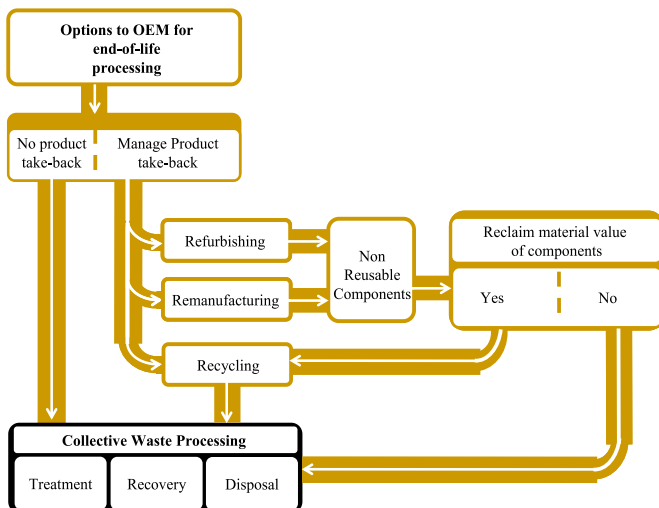
- t = service time of a product (usually in units of Mh if the units for λ are as below)
- λ = degradation rate (failure/Mh − IEC-62380, 2004)
- L = labour rate
- f = disassembly factor
- T_d = time to completely disassemble a product
- T_a = time to completely assemble a product

4.5.2. Remanufacture

Like refurbishment, remanufacture primarily addresses components within a product that are not up to specification (StEP, 2009). A remanufactured part or component will generally conform to a higher specification. According to Zussman et al. (1994), if a product's component life expectancy is less than twice that of the product life expectancy, then it may be the cause of product failure even after repair. This will diminish the value of the product for reuse. Therefore, to ensure that a remanufactured product is of at least the same reliability as a newly manufactured product, any target components with a component/product life ratio of two or less must be attended to, for either remanufacture or replacement. The profit and cost of remanufacture is estimated using the following equation. For the remanufacturing cost, the whole expense for remanufacture using the retired parts is given by Shu and Flowers (1999):

$$
\begin{aligned}
C_{rm} = & ((T_d + T_a) \cdot L \cdot f) + \left(P_f \cdot C_f\right) \\
& + \left(\left(P_{pd} + P_f \cdot P_{pe} - P_{pd} \cdot P_f \cdot P_{pe}\right) \cdot C_p\right)
\end{aligned}
\tag{3}
$$

where

- C_{rm} = remanufacturing cost
- T_d = disassembly time
- T_a = assembly time
- L = labour rate
- P_f = probability of fastener failure in disassembly and assembly
- C_f = cost of fastener failure
- P_{pd} = probability of part failure in disassembly and assembly
- P_{pe} = probability of part failure in fastener-method extraction
- C_p = cost of part failure
- f = disassembly factor

It should be noted that, a product intended for upgrade may require a process similar to remanufacture. In the case where discrete components are directly exchanged for upgraded components of the same function then these simply count as a component being replaced. If the upgrade is expected to include significant redesign then the additional cost cannot be analysed since the upgraded design has not yet happened.

4.5.3. Recycle

To reclaim material value within the EOL product, it is assumed that components made from or containing valuable material are of interest. These components are therefore targeted and removed from the product via disassembly. The condition of the removed components is not important as the recycler is only interested in the material content. The value of the component is the price that the recycler is willing to pay for it per mass of the desired material (Gonzalez and Adenso-diaz, 2005). For target components that only partially contain valuable material, the material weight is obtained from supplier data. The profit and cost of recycling the product is estimated using the following equations. For recycling cost, the whole expense to recycle the retired parts is given by Dantec (2005):

$$
\begin{aligned}
\text{Recycling cost} &= RV_i − RC_i \\
RV_i &= (\text{Parts}_i \cdot MV_m − Oc_i) \cdot W_i \\
RC_i &= RT_i \cdot f \cdot L
\end{aligned}
\tag{4}
$$

where

- Parts_i = the number of parts of type i
- W_i (kg) = the weight of type i parts
- MV_m (GBP/kg) = the mass material value of the parts
- RT_i (h) = the time necessary to remove one type i part, and
- Oc_i (GBP/kg) = opportunity cost/kg
- f = disassembly factor
- L (GBP/h) = the hourly wage

Recycling can also be used in conjunction with refurbishment and remanufacture, for example, non-reusable components removed with material value are sent to be recycled. This implies no further disassembly and only increases the revenue from those processes by the price the recycler is willing to pay.

4.5.4. Collective waste processing

Under the WEEE directive OEMs are obliged to take on the finance of treatment, recovery, recycling and safe disposal of their EEE at EOL. In all member states, a collective approach has been adopted. For either B2B or B2C EEE, cost of treatment and recovery is determined by mass. The cost of treatment per product can therefore be calculated based on the treatment rate per product category.
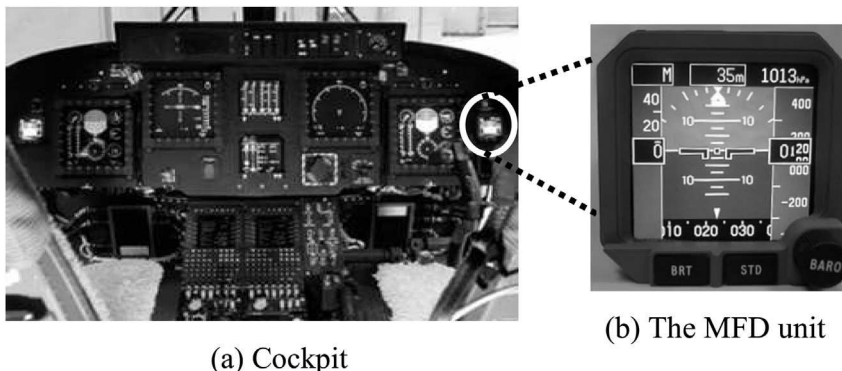

(a) Cockpit

(b) The MFD unit

Fig. 6. Multi-functional display unit (MFD).

5. A case study

An exemplar product is evaluated to demonstrate how the proposed cost estimating approach may be implemented. A program was written in Microsoft Excel Visual Basic to aid the calculation of disposal costs. The costs to refurbish, remanufacture and recycle a multi-functional display unit (MFD) (Fig. 6) were estimated. Target components were located within the BOM and a disassembly depth factor was calculated. The estimated cost to refurbish the product with good and failed condition target components was assumed to be available.

Three target components have been identified for the purpose of this case study: (1) heat sink, memory SDRAM (synchronous dynamic random access memory) chip and a transformer. These components are found in the *module* and *backlight driver* assemblies respectively which have been identified in the BOM structure as shown in Fig. 7.

From analysing the BOM structure in Fig. 7, it can be determined that there are 8 assemblies and 5 assemblies to disassemble. Therefore the disassembly depth factor is:

$$f = 5/8 = 0.63$$

Data required for the key input variables for the above equations can be obtained as described below.

- The P_i represents the number of selected parts/components to be analysed for EOL.
- The weight of individual selected parts (W_i) was taken directly from the suppliers.
- The mass material value of parts (MV_m) was calculated by finding the value of 1 t of scrap. For example, aluminium alloy, plastic, which was GBP 729 and GBP 795 respectively (Greengatemetals, 2014) and dividing the value by 1000, as the required units are GBP/kg.
- A reasonable assumption of the time to remove the part (RT_i) was made from personal knowledge, assuming that the individual removing the parts is a competent.
- The opportunity cost (Oc_i) was calculated by discovering the shredder value (Greengatemetals, 2014), which was GBP 125/t, and dividing this by 1000 to scale this value to per kg, and multiplying this by the weight of the component.
- The labour rate (L) was taken from UK standard wages.

- The disassembly depth factor (f) was calculated as explained in Section 4.3.1.
- Cost to repair/refurbish or remanufacture the device with a component in good condition (C_{good}) — this cost depends on the component of interest and would be predicted using cost of labour rate or intuitive information.
- Cost to repair/refurbish, remanufacture or replace the device with a component that has failed ($C_{failure}$) — this cost is predicted as it is with C_{good}. However, if the component of interest is not expected to be fixable from a failed condition, then the cost to purchase (replace) the component is used for highest possible refurbishment cost.
- The time to complete the assembly process (T_d) and time to complete the disassembly process (T_a) was an assumption made from personal knowledge.
- The expected life time of a product (t) converted into h and divided by 1,000,000.
- The failure rate/1,000,000 (λ) was sourced from the reliability prediction of electronic equipment (IEC-62380, 2004) and applied to these case studies.
- The probability of fastener failure in the disassembly and assembly process (P_f) for the parts in the case study was 0.01: a very low risk if the fasteners are kept in good condition (as specified by the manufacturer). The cost of the fastener failure (C_f), was taken directly from an electronic component supplier (Greengatemetals) which is 0.085 GBP i.e. the calculation uses 0.085 GBP/rivet and multiply by the number that required for a part.
- The probability of the part failing (assuming at it has not failed before removal) during the disassembly and assembly process (P_{pd}) is very low for both items as the item is removed carefully by someone competent; therefore an assumption of 0.0001 (0.1%) was made.
- The probability of part failure in the fastener method of extraction (P_{pe}), which assumes a one way fixing system such as a rivet, is used, and as no rivets or other one way systems are used in either assembly, a value of 0 was used.
- The cost of part failure (C_p) was taken directly from the distributor.

The software is able to calculate $C_{refurbish}$ automatically (see Fig. 8). When used with a spreadsheet or database of the product
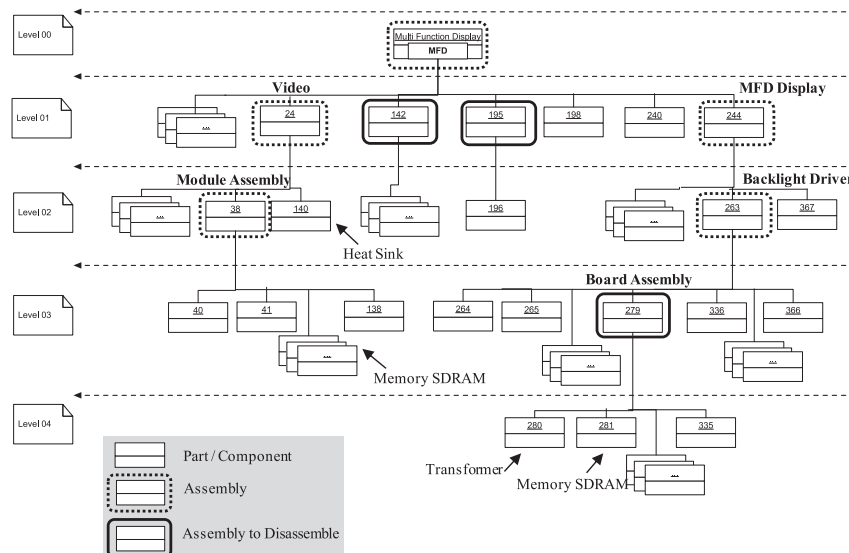

Fig. 7. Illustrative representation of product breakdown for cost evaluation.

BOM, the user can filter for target components and export them as a list into the program spreadsheet. C_{good}, $C_{failure}$ and λ must be entered for each target component. Values for t, L, T_a and T_d need only be entered once as these are fixed values per product. Table 1 presents the input data required and the resulting EOL cost comparisons. The resulting mapping of each targeted component is shown in Fig. 9 and the cheapest route of the EOL costs of the targeted parts in the MFD are, for example, (i) one heat sink with recycling cost GBP 8.98; (ii) two memory SDRAMs with recycling cost GBP 18.7 and (iii) one transformer with recycling cost GBP 8.5. Thus, this result will enable the product designer to make firm decisions at the design stage over the actions at EOL. Although the recycling costs of this system are very low and may seem like the most economically viable solution, however, with high costs of energy, the overall recycling cost to return the materials into something useful is high. The scrap value sale would also be of low value, making this a reasonable and viable process if the other three are unavailable, or it's beyond any point of reuse.

6. Conclusion and future work

Traditionally, OEMs have ignored the destiny of their products at EOL. In the age of extended producer responsibility (EPR), more OEMs are embracing a lifecycle approach to product EOL. For example: Lee et al.'s (2014) design for EOL approach and Fukushige et al.'s (2012) method on lifecycle scenario for product EOL strategy. The WEEE directive was introduced in 2005 as part of a large policy mechanism aimed at implementing the EPR concept in Europe by making manufacturers of EEE legally responsible for the recovery and recycling of their products at EOL.

Based on the research finding, many studies of EOL cost models used a detailed approach and examining products at component level (Fan et al., 2013). This kind of approach requires greater design detail that may not be available at the concept design stage. From the research presented in this paper, a novel approach to predicting EOL costs of EEE was developed. The proposed method is a flexible cost model that can be applied to all the major EOL recovery process options. The cost model offers a manageable and realistic solution so that the OEM can estimate the cost of potential EOL recovery processes at the concept design stage. In this model, a top-down and bottom-up analysis of the product is made and cost elements

Table 1
EOL cost evaluation.

Notation	SI unit	Heat sink	Memory SDRAM	Transformer
Parts$_i$	–	1	2	1
W_i	kg	0.54	0.022	1.5
MV$_m$	GBP/kg	0.795	0.35	0.795
Rt$_i$	h	1	2	2
Oc$_i$	GBP/kg	0.068	0.0028	0.186
L	GBP/h	15	15	15
f	–	0.625	0.625	0.625
C_{good}	GBP	15	15	15
$C_{failure}$	GBP	50	350	950
t	h/10^6	0.122	0.11	0.122
λ	–	1.2	1.2	1.2
T_d	h	1	2	2
T_a	h	1	2	2
P_f	–	0.01	0	0.01
C_f	GBP	0.34	0	0.34
P_{pd}	–	0.0001	0.0001	0.0001
P_{pe}	–	0.0001	0	0.0001
C_p	GBP	50	350	950
EOL cost comparisons				
Recycle		9.0	18.7	8.5
Refurbish		38.5	98.1	179.8
Remanufacture		18.8	37.5	37.6

are evaluated at product, assembly and component level. In the case study, the costs to refurbish, remanufacture and recycle of a multi functional display unit were calculated. This proposed method is an uncomplicated, inexpensive approach that is flexible to suit any EOL processing intentions.

The approach does not account for future uncertainty. Given that the model estimates future costs that will inform decision making today, discounting effects should be incorporated and a 'net present value' should be used. In the calculation for recycling profit, forecasting techniques may be helpful in predicting the value of applicable materials, e.g. gold in a circuit board, at the time of expected product EOL. If a small change in the price of gold results in a large change in profit margin then the viability of the recycling operation is very sensitive to the price of gold and a higher discount rate should be used to account for this risk. Further work is that since the proposed approach has simplified the time taken for disassembly, for example, if a component or subsystem fixed with 50 screws and a component fixed with quick joints. A new method
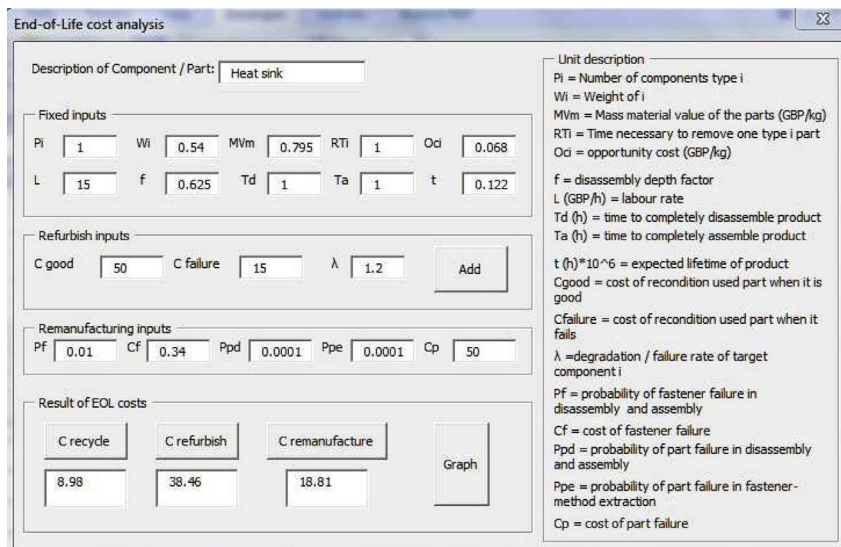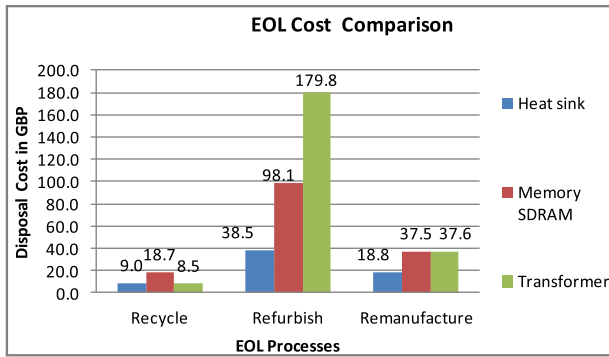

Fig. 8. The EOL software GUI.

Fig. 9. Example software calculations.

needs to be developed to quantify this disassembly time so that more accurate cost estimation can be obtained.

There are many external factors in deciding which EOL recovery process should be used for a given product, such as product evolution rate, market characteristics and so on. The proposed cost models only address the viability of the EOL process itself so cannot be used alone in the decision of a most appropriate EOL process strategy. However, since the cost models allow for direct cost comparison between the EOL processes, future work could develop the cost models to be used to compliment the evaluation of all these factors in deciding the most appropriate EOL recovery process strategy.

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Appendix A. Supplementary material

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2014.10.033.

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