EDAS

by Feri Afrinaldi

Submission date: 07-Aug-2021 02:05PM (UTC+0800)
Submission ID: 1628676512
File name: afrinaldi2010.pdf (1.39M)
Word count: 6971
Character count: 37224

Int. J. Sustainable Design, Vol. 1, No. 3, 2010 257

EDAS: Software for End-of-Life Disassembly Analysis

Feri Afrinaldi*

Faculty of Engineering,
Department of Industrial Engineering,
Andalas University,
Limau Manis, Padang – 25163, Indonesia
E-mail: feri_afrinaldi@ft.unand.ac.id
*Corresponding author

Muhamad Zameri Mat Saman
and Awaluddin Mohamed Shaharoun

Faculty of Mechanical Engineering,
Department of Manufacturing and Industrial Engineering,
University Teknologi Malaysia,
81310 Skudai, Johor, Malaysia
Fax: +607-5566159
E-mail: zameri@fkm.utm.my
E-mail: awal@fkm.utm.my

Abstract: In recent years, many countries have developed legislations which are aimed to force manufacturers to recycle their products at the end of their life. However, before end-of-life products can be recycled, end-of-life disassembly needs to be in place. It entails large amounts of capital expenditure and time. Besides this, product designers also do not have experience in disassembling and recycling to determine the impact of various design aspects on difficulty at the disassembly stage. Therefore, there is a need for a tool to analyse the disassemblability and recyclability. This paper proposes software named as EDAS to fulfil those needs.

Keywords: disassembly; disassemblability; disassembly sequence; end-of-life; recycling.

Reference to this paper should be made as follows: Afrinaldi, F., Saman, M.Z.M. and Shaharoun, A.M. (2010) 'EDAS: Software for End-of-Life Disassembly Analysis', *Int. J. Sustainable Design*, Vol. 1, No. 3, pp.257–277.

Biographical notes: Feri Afrinaldi is a Lecturer in the Department of Industrial Engineering of Andalas University, Indonesia. He is currently pursuing his Master's Degree in the Department of Manufacturing and Industrial Engineering, Universiti Teknologi Malaysia (UTM). His research interests include disassembly and recycling of complex products and reliability modelling.

Muhamad Zameri Mat Saman is a Senior Lecturer in the Department of Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM). He received his PhD in

Mechanical Engineering from Coventry University, UK. His current research interests are sustainable development, product life cycle, manufacturing system and industrial engineering.

Awaluddin Mohamed Shaharon is a Professor in the Department of Manufacturing and Industrial Engineering, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM). He received his PhD in Computer Integrated Manufacturing from Loughborough University of Technology, UK. His research interests are in the areas of computer integrated manufacturing, enterprise integration modelling techniques and information systems, supply chain management and product innovation.

---

1 Introduction

Special interest has been addressed to the impacts of disposal of products at the end of their life. This is due to the tremendous growth in the demand for consumer products that have resulted shortened lifetime of most products. In the case of electronic products, the US Environmental Protection Agency (EPA) estimates that about 40 million computers became obsolete in a year and only 18% of them are recycled, the rest are still disposed of, primarily in landfills (EPA, 2008). Conversely, the number of potential landfill sites has seen an exponential decrease (Desai, 2002).

In order to reduce the environmental impacts of end-of-life products, European Union, Japan, USA, and other countries require manufacturers to take back their products at the end of their useful life and recycle them. In Europe, the End-of-Life Vehicle Directive (ELVD) has currently been transposed into national legislation and enacted (The European Parliament and of the Council of European Union, 2000). In other countries of the world, similar legislation can be found or is planned to be enacted, such as the Electronic Waste Recycling Act of 2003 in California and Japan's Home Appliance Recycling Law.

Based on Desai (2002), before end-of-life products can be recycled, end-of-life disassembly needs to be in place. These entail large amounts of capital expenditure. Most manufacturers would not like to even consider disassembling, reusing, recycling and remanufacturing unless costs are justified and financial gains are assured. In general, most designers of today also do not seem to have required experience in disassembling and recycling to determine the impacts of various design aspects on disassemblability at the end-of-life stage. It is, therefore, important that a system for evaluating the disassemblability is available in order to encourage manufacturers to incorporate disassembly issues when developing a product. It will aid them in fulfilling the legislation that will be fully implemented and at the same time the costs of disassembly are justified and financial gains are assured.

This paper proposes a software tool named EDAS which integrates the determination of end-of-life options, disassemblability evaluation, and searches for the optimum disassembly sequence to assess the design of products for their technical and economic viability at the end-of-life.

2 Literature review

According to Rose and Stevels (2001), end-of-life is the point in time when the product no longer satisfies the initial purchaser or first user. Several researches have been conducted in order to aid product designers to select the appropriate end-of-life options for their products. Rose and Stevels (2001) proposed an End-of-Life Strategy Environmental Impact Model (ELSEIM) to calculate environmental impact across all possible end-of-life strategies. Lye et al. (2002) designed Environmental Component Design Evaluation (ECoDE). It uses the Analytical Hierarchy Process (AHP) to compare criteria in assessing the environmental impact of a product. Although ECoDE can estimate the end-of-life value, no guideline has been provided to product designers for selecting the appropriate end-of-life options. Lee et al. (2001) proposed a complete guideline for determining feasible end-of-life options. The guideline was developed based on the material composition of the component. For each option, authors also proposed a method to calculate the end-of-life value.

In the area of disassemblability evaluation, various methodologies have been developed to evaluate the disassemblability of a product. Yi et al. (2003) proposed a method for evaluating disassembly time. In this work, the disassembly time is divided into preparation time, moving time, disassembly time, and post-processing time. But some of the time phases which were developed in this method, such as preparation time, may not directly affect the disassembly efficiency. Desai and Mital (2005) presented a methodology to design products for disassembly. According to this, disassemblability is a function of several factors, such as effective tools placement, weight, size, material and shape of the components. In order to measure the disassembly time, the authors only focus on the operations which directly affect the disassembly efficiency. Design attributes, design parameters and the detailed description of the working environment were provided to aid the designers in selecting the disassemblability score.

In order to find the optimal disassembly sequences, several methods can be used. Dong et al. (2006) presented a novel approach to the automatic generation of disassembly sequence from a hierarchical attributed liaison graph representation of an assembly by recursively decomposing assembly into sub-assemblies. Disassembly for selected components often occurs during product end-of-life treatment. Considering this, Wave Propagation (WP) method was proposed to determine the optimal disassembly sequence (Mascle and Balasoiu, 2003). Lambert (1999) used binary linear programming to find the optimal disassembly sequence. The binary linear programming model can be directly derived from the AND/OR graph. In order to avoid long CPU computing time, the binary linear programming model can be relaxed into a continuous linear programming problem. This is possible because the basic solution of the linear programming model is an extreme point of a polyhedron. It turns out that the model is simple and flexible indeed. Changing the model only requires the modification of transition matrix, new cost and new revenue vector. Kongar and Gupta (2006) presented a genetic algorithm-based approach to find an optimal disassembly sequence. The objective function of this genetic algorithm is to minimise the disassembly time. The chromosome in this genetic algorithm represents the disassembly task sequence, disassembly direction, method, demand (for recycling or not) and material. The Precedence Preservative Crossover (PPX) method is used to satisfy disassembly precedence relationships. The application of ant colony optimisation can be found in Shan et al. (2007). The advantage of the genetic algorithm model, ant colony optimisation and other meta-heuristic methods is that they can deal with a lot of complicated problem that cannot be solved by using mathematical programming methods but they need specialised software to solve the problem, relatively long CPU times, generating of a sub-optimum solution without any knowledge of its distance from optimum, and restricted gain of insight in the problem.

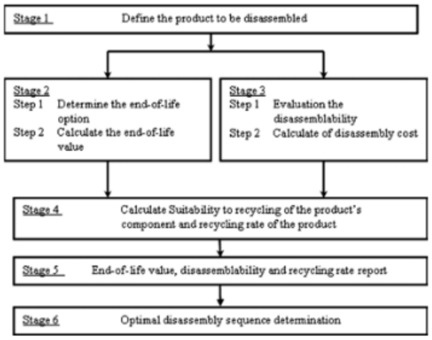
The above review shows that researchers studied end-of-life option determination, disassemblability evaluation and disassembly sequencing as separate parts. Only a few researchers conducted research to integrate the analyses of disassembly sequencing and disassemblability evaluation in one framework. There is a bulk of researches in terms of disassembly sequencing optimisation with a particular objective function, such as minimisation of cost or minimisation of time by using mathematical models, but certain physical and practical factors cannot be effectively incorporated into mathematical models. In addition, the allocation of certain end-of-life options also plays an important role in the disassembly process. Mathematical models also fail to consider these factors.

These three factors, end-of-life option determination, disassemblability evaluation and disassembly sequencing, are important. The end-of-life option determination and the disassemblability evaluation will show how economically efficient it is to disassemble a product and check the potential of a component to be recycled. The optimum disassembly sequence will maximise the end-of-life value and minimise the disassembly cost of the end-of-life products.

3 Methodology

The methodology which is implemented in EDAS integrates the determination of the end-of-life options, disassembly sequencing and the evaluation of disassemblability within a single framework. The proposed methodology is shown in Figure 1. It will be a very useful tool for manufacturers in minimising the environmental impacts of end-of-life product, maximising economic value of end-of-life product and complying with end-of-life product legislation.

Figure 1 Methodology



In stage 1, the product being disassembled is defined. It means obtaining the type and quantity of fasteners among product's components, mass of the components, materials used, and disassembly tasks required to take apart the components from the product.

In stage 2, the end-of-life options for the components are obtained. The method proposed in Lee et al. (2001) is adopted. If the component:

- Is made from metal without any other alloy, primary recycling is recommended. If alloys are present, they alter the mechanical properties of the parent metal, so secondary recycling or landfill is more appropriate.
- Is polymeric, primary recycling is recommended, otherwise consider secondary recycling or incineration to recover its energy content.
- Is made from ceramic, secondary recycling or landfill is recommended.
- Is made from an elastomeric or is a composite material, secondary recycling or incineration is recommended, otherwise landfill.
- Contains toxic or hazardous material, special handling is required.

In order to calculate the end-of-life value, the equations below are used (Lee et al., 2001):

$$\text{Reuse value} = \text{Cost of component (\$)} - \text{Miscellaneous cost (\$)} \tag{1}$$

$$\text{Remanufacture value} = \text{Cost of component (\$)} - \text{Remanufacture cost (\$)} - \text{Miscellaneous cost (\$)} \tag{2}$$

$$\text{Primary recycle value} = \text{Weight of component (kg)} \times \text{Market value of material (\$/kg)} - \text{Miscellaneous cost (\$)} \tag{3}$$

$$\text{Secondary recycle value} = \text{Weight of component (kg)} \times \text{Scrap value of material (\$/kg)} - \text{Miscellaneous cost (\$)} \tag{4}$$

$$\text{Incinerate value} = \text{Energy produced (KJ)} \times \text{Unit cost of energy (\$/KJ)} - \text{Miscellaneous cost (\$)} \tag{5}$$

$$\text{Landfill cost} = -(\text{Weight of component (kg)} \times \text{Cost of landfill (\$/kg)}) - \text{Miscellaneous cost (\$)} \tag{6}$$

$$\text{Special handling cost} = -(\text{Weight of component (kg)} \times \text{Cost of special handling (\$/kg)}) - \text{Miscellaneous cost (\$)} \tag{7}$$

$$\text{Miscellaneous cost} = \text{Handling} + \text{Transportation} + \text{Storage} + \text{Re-processing}. \tag{8}$$

In stage 3, the disassemblability of product is evaluated. The disassemblability evaluation method proposed by Desai and Mital (2005) is used. The scoring system, which is derived from the MTM time measurement technique, is used to show the disassemblability of product. By using the scoring system, disassembly time can be estimated. Multiplying the estimated disassembly time with disassembly operation rate per unit of time will yield the disassembly cost.

In stage 4, recycling rate is computed. It is aimed to evaluate whether the design meets the legislation or not. Recycling rate is the share of materials (in percent by weight) out of all materials used in the product, which may be recycled at feasible and reasonable expenditure. Equations (9) and (10) are used to calculate the recycling rate (BMW Group, 2002).

$$R_Q = \frac{M_{R1} + M_{R2}}{M_G} \times 100\% \tag{9}$$

M_{R1}, M_{R2} = Mass (kg) of components for recycling rate categories R1 and R2.
M_G = Mass (kg) of product or subassembly.

Recycling categories (R1, R2 and R3) are defined as:

- R1 – Components suitable for economic recycling with SR ≥ 100%.
- R2 – Component suitable for economic recycling which has 80% ≤ SR < 100%.
- R3 – Not suitable for economic recycling with SR < 80%.

Suitability for recycling (SR) is calculated as follow:

$$\text{Suitability for recycling} = \frac{\text{Cost (equivalent new material + disposal)}}{\text{Cost (dismantling + re-processing + logistics)}} \times 100\%. \tag{10}$$

In stage 5, the reports of the end-of-life value calculation, disassemblability evaluation and recycling rate are provided. By using these reports, the decision to redesign can be made.

In stage 6, the disassembly sequence is optimised. It will maximise the end-of-life value and minimise the disassembly cost through searching the best sequence. The disassembly sequence problem is formulated into a linear programming model (Lambert, 1999), as shown in equations (11)–(13).

$$\text{Maximise}: \mathbf{Z} = (\mathbf{rT} - \mathbf{c})\mathbf{x} \tag{11}$$

$$\text{Subject to}: \mathbf{Tx} \le \mathbf{0} \tag{12}$$

$$\mathbf{x} = \{0 \text{ or } 1\} \tag{13}$$

where **r** is the revenue vector (end-of-life value), **c** is the disassembly cost vector, **T** is the transition matrix. The decision variable (disassembly operations) is **x** which has binary value {0 or 1}. This indicates whether a disassembly action should be executed (1) or not (0).

According to Lambert and Gupta (2005), the revenues are related to the availability of the sub-assemblies. These revenues can be grouped into a revenue vector **r** with components r_i. These might have positive and negative values, because the availability of a specific subassembly may represent costs when it cannot be reused or recycled and has to be disposed at some expense. The disassembly costs are assigned to the disassembly operations, and this is represented via the cost vector **c** with components c_j. Costs are only encountered if the action is actually performed, which is only true if the corresponding disassembly operation variable is equal to 1.

The transition matrix is derived from the AND/OR graph. Based on Lambert and Gupta (2005), in AND/OR graph, sub-assemblies are used as nodes and every disassembly operation is represented by a hyper-arc that points from parent sub-assembly to children sub-assemblies (AND relationship). Because a sub-assembly can typically be disassembled in several ways, it results in different hyper-arcs pointing from the sub-assembly (OR relationship).

According to Lambert (1999), each of transition matrix's columns corresponds to an action and each of its rows to a sub-assembly. Destruction or creation of a sub-assembly by this action is indicated by assigning the value –1 or +1 to the element on the corresponding row. All other elements are zero.

4 Assumption

The application of the above methodology is limited by several assumptions:

- In computing the end-of-life value it is assumed that the recycling facility has 100% efficiency.
- The disassembly cost is assumed as the labour cost per unit of time.
- As mentioned earlier that Method Time Measurement (MTM) System was used in estimating the disassembly time. Here, in using this method, it is assumed that the disassembly operations is performed sitting down at the bench level.
- The operators doing the disassembly operations are assumed have average skill and work in the normal condition.
- The material of the components used for developing the product is known.

5 EDAS: End-of-Life Disassembly Analysis Software

Based on the above methodology, computer software named as EDAS was developed to ease the tasks of disassembly analysis and facilitate the decision making.

In order to illustrate the application of the proposed methodology and the software developed for disassembly evaluation, a hair clipper, shown in Figure 2, was used as a case study.

Figure 2 Hair clipper (see online version for colours)

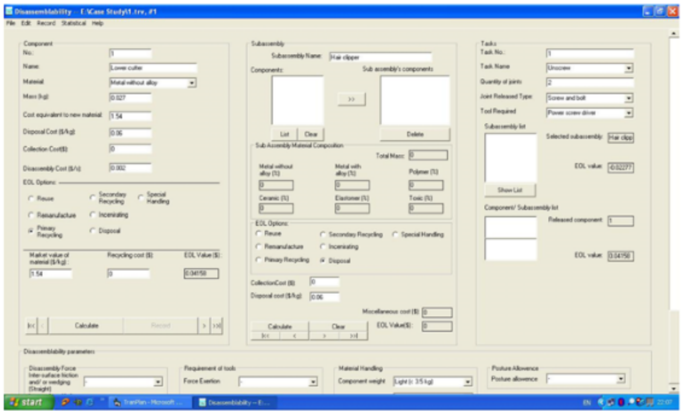
Note:

1.	Lower cutter	8.	Magnet
2.	Upper cutter	9.	Coil
3.	Tip	10.	Outer switch
4.	Handle	11.	Inner switch
5.	U-Shape	12.	Cable
6.	Upper cover	13.	Lower cover
7.	Front part		

Stage 1: *Product definition*

Figure 3 is the template for entering the product's and components' information. The information entered into this template comprises component's number, component's name, mass and costs. For the sub-assemblies, the information entered comprises the sub-assemblies and the components used for developing them. For disassembly tasks, the information entered comprises task number, task name, joint released, joint released type and the tools required to perform the task.

Figure 3 Template for disassemblability evaluation input (see online version for colours)



Component
No.: 1
Name: Lower cutter
Material: Metal without alloy
Mass (kg): 0.027
Cost equivalent to new material: 1.54
Disposal Cost ($/kg): 0.06
Collection Cost($): 0
Disassembly Cost ($/s): 0.002
EOL Options: ○ Reuse ○ Secondary Recycling ○ Special Handling ○ Remanufacture ○ Incinerating ● Primary Recycling ○ Disposal
Market value of material ($/kg): 1.54
Recycling cost ($): 0
EOL Value ($): 0.04158

Subassembly
Subassembly Name: Hair clipper
Components:
Sub assembly's components
Sub Assembly Material Composition
Total Mass: 0
Metal without alloy (%): 0
Metal with alloy (%): 0
Polymer (%): 0
Ceramic (%): 0
Elastomer (%): 0
Toxic (%): 0
EOL Options: ○ Reuse ○ Secondary Recycling ○ Special Handling ○ Remanufacture ○ Incinerating ○ Primary Recycling ● Disposal
CollectionCost ($): 0
Disposal cost ($/kg): 0.06
Miscellaneous cost ($): 0
EOL Value($): 0

Tasks
Task No.: 1
Task Name: Unscrew
Quantity of joints: 2
Joint Released Type: Screw and bolt
Tool Required: Power screw driver
Subassembly list
Selected subassembly: Hair clipp
EOL value: -0.02277
Component/ Subassembly list
Released component: 1
EOL value: 0.04158

Disassemblability parameters
Disassembly Force Inter-surface friction and/ or wedging (Straight): -
Requirement of tools
Force Exertion: -
Material Handling
Component weight: Light (< 3.5 kg)
Posture Allowance
Posture allowance: -

Stage 2: End-of-life option determination and end-of-life value calculation

The template shown in Figure 3 is also used to select and compute the end-of-life value of the components and sub-assemblies. As an illustration, a lower cutter is discussed. Based on the proposed methodology, feasible end-of-life option for sheet metal (material composing lower cutter) is primary recycling. The market value of metal is 1.54 $/kg (this amount is assumed to be the result of forecasting and present value calculation). Since miscellaneous costs are outside the control of the designers, they are omitted from the calculation.

$$\begin{aligned}\text{Primary recycling value} &= \text{Weight of component (kg)} \times \text{Market value of material (\$/kg)} - \text{Miscellaneous cost (\$)}\\ &= 0.027\text{ kg} \times 1.54\text{ \$/kg} = \$\ 0.042.\end{aligned}$$

Table 1 shows the end-of-life value of the hair clipper's components. It shows that all components of the hair clipper give rise to a surplus and do not adversely impact the environment. A component which adversely impacts the environment will require special handling and the deficit incurred by special handling is indicated by the negative sign of the end-of-life value.

Table 1 End-of-life value of the hair clipper's components

No.	*Component*	*Mass* (kg)	*Material*	*EOL option*	*EOL value* ($)
1	Lower cutter	0.027	Sheet metal	Primary recycling	0.04158
2	Upper cutter	0.008	Sheet metal	Primary recycling	0.01232
3	Tip	0.0005	Polypropylene	Secondary recycling	0.00001
4	Handle	0.002	Polypropylene	Secondary recycling	0.00004
5	U-shape	0.008	Sheet metal	Primary recycling	0.01232

Table 1 End-of-life value of the hair clipper's components (continued)

No.	*Component*	*Mass* (kg)	*Material*	*EOL option*	*EOL value* ($)
6	Upper cover	0.021	Polypropylene	Secondary recycling	0.00042
7	Front part	0.002	Sheet metal	Primary recycling	0.00308
8	Magnet	0.027	Metal	Primary recycling	0.04158
9	Coil	0.154	Cooper	Primary recycling	0.23716
10	Outer switch	0.001	Polypropylene	Secondary recycling	0.00002
11	Inner switch	0.004	Polypropylene	Secondary recycling	8×10^{-5}
12	Cable	0.08	Cooper	Primary recycling	0.1232
13	Lower cover	0.045	Polypropylene	Secondary recycling	0.0009

Stage 3: Disassemblability evaluation

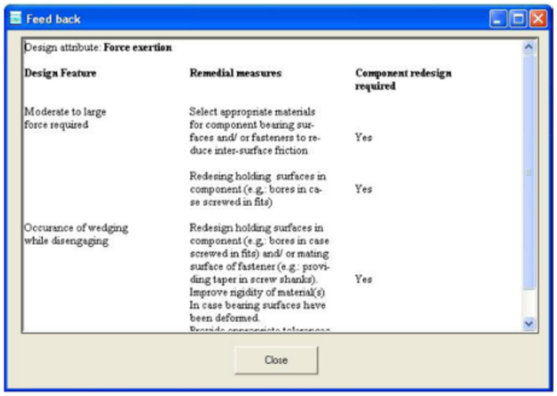
Here, numerical disassemblability evaluation is obtained. Table 2 shows the numerical disassemblability analysis of unscrews operation for disassembling the lower cutter which has 2 screws. From Table 2, it can be seen that force as the design attribute or parameter of design is the highest contribution to the duration of disassembly time of the lower cutter. In order to reduce the exertion of force required to disengage the lower cutter, according to Desai and Mital (2005), appropriate materials for component bearing surfaces and/or fasteners should be selected to reduce inter-surface friction. Besides, the holding surfaces in the component also need to be re-designed. The software developed also provides redesign recommendations in order to increase the disassemblability of the product analysed.

Table 2 Disassemblability evaluation of lower cutter

Design attribute	*Design attribute parameter*	*Score*
Force	Straight line and twisting motions with exertion of pressure/inter-surface friction and/or wedging	3
Material handling	Component dimensions	2
	Magnitude of weight	2
	Symmetric components are easy to handle	0.8
Requirement of tools	Exertion of torque	2
Accessibility	Dimensions/length, breadth, depth, radius, angle made with surface	1
	Location/on plane surface	1
Positioning	Symmetry	1.2
Total		*13*
Disassembly time = Number of screws × Total × 10 × 0.036 = 2 × 13 × 10 × 0.036 = 9.36 s.		
Disassembly cost = Disassembly time (s) × Labour cost ($/s) = 9.36 × 0.002 = $ 0.01872		

As an example, redesign recommendation for exertion of force as the design parameter is shown in Figure 4. Based on Figure 4, a variety of alternative design configurations can be generated corresponding to each remedial measure. Each of these configurations may, in turn, be analysed for cost effectiveness and, in turn, tested for functionality, assemblability, manufacturability and structural rigidity under working conditions (Desai, 2002). Table 3 shows all disassembly tasks and their duration. Template shown in Figure 3 is also used to evaluate the disassemblability and estimate the disassembly time.

Figure 4 An example of redesign recommendation (see online version for colours)



Design attribute: **Force exertion**

Design Feature	**Remedial measures**	**Component redesign required**
Moderate to large force required	Select appropriate materials for component bearing surfaces and/ or fasteners to reduce inter-surface friction	Yes
	Redesing holding surfaces in component (e.g.: bores in case screwed in fits)	Yes
Occurance of wedging while disengaging	Redesign holding surfaces in component (e.g.: bores in case screwed in fits) and/ or mating surface of fastener (e.g.: providing taper in screw shanks). Improve rigidity of material(s) In case bearing surfaces have been deformed.	Yes

Table 3 Disassembly tasks and their duration

No.	*Released component*	*Task*	*Tool*	*Duration* (s)
1	Lower cutter	Unscrew	Screwdriver	9.36
2	Upper cutter	Pull	–	3.42
3	Tip	Pull	–	3.42
4	Handle	Unscrew	Screwdriver	5.04
5	U-shape	Pull	–	3.42
6	Upper cover	Unscrew	Screwdriver	18.72
7	Front part	Unscrew	Screwdriver	9.36
8	Magnet	Pull	–	4.14
9	Coil	Unscrew	Screwdriver	9.36
10	Outer switch	Pull	–	3.42
11	Inner switch	Pull	–	3.42
12	Cable	Pull	–	3.78
13	Lower cover	Pull	–	3.78

Stage 4: Recycling rate calculation

In stage 4, recycling rate is obtained. Before recycling rate can be calculated, Suitability for Recycling (SR) must be calculated earlier.

As an example, the suitability for recycling of the lower cutter is explained. The cost of equivalent new material = mass (kg) × cost of equivalent new material of lower cutter ($/kg) = 0.027 × 1.54 = $0.04158, disposal cost = mass (kg) × disposal cost per kg

(\$/kg) = 0.027 × 0.06 = \$0.00162, dismantling cost = disassembly time (s) × disassembly rate (\$/s) = 9.36 × 0.002 = \$0.01872, re-processing cost and logistic cost are omitted from the calculation because they are outside the control of the designers.

$$SR = [(0.04158 + 0.00162)/0.01872] \times 100\% = 230.77\%.$$

It means that, if the lower cutter is not recycled the total cost of new material for producing a new lower cutter plus cost required disposing the end-of-life lower cutter is 2.3077 times as much as the total cost (disassembly, reconditioning and logistic) required if it is recycled. Based on this, it is better if the lower cutter is recycled. Table 4 presents the suitability of recycling for all components of a hair clipper.

Table 4 Suitability for recycling and recycling category of hair clipper's components

No.	*Released component*	*Suitability for recycling* (%)	*Category*
1	Lower cutter	230.77	R1
2	Upper cutter	187.13	R1
3	Tip	0.58	R3
4	Handle	1.59	R3
5	U-shape	187.13	R1
6	Upper cover	4.49	R3
7	Front part	17.09	R3
8	Magnet	521.73	R1
9	Coil	1316.24	R1
10	Outer switch	1.17	R3
11	Inner switch	4.68	R3
12	Cable	1693.12	R1
13	Lower cover	47.62	R3

Based on recycling category of each component, recycling rate can be calculated. The total mass of the hair clipper is 0.3795 kg and the total mass of the components with $R1$ and $R2$ category is 0.304 kg.

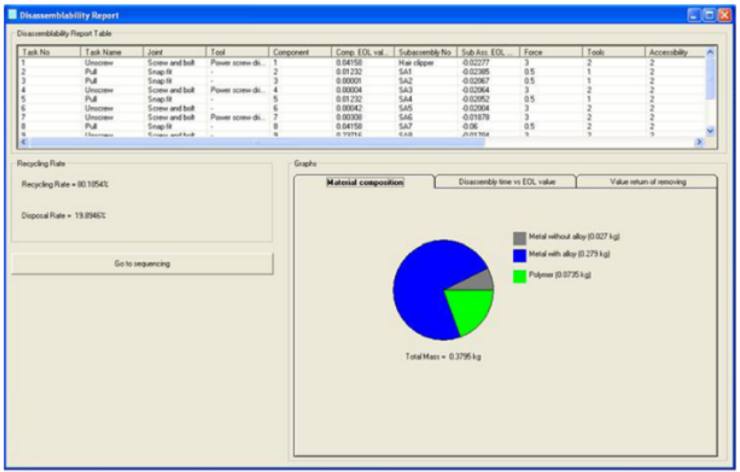
$$\text{Recycling rate} = (0.304/0.3795) \times 100\% = 80.1\%.$$

It means that, 80.1% (in terms of weight) out of all the materials used in the hair clipper can be recycled at feasible and reasonable expenditure.

Stage 5: End-of-life values, disassemblability, and recycling rate report

Here, the disassemlability evaluation reports are provided. Figures 5–7 show the reports. In Figure 5 the disassemblability report table is provided. It aims to show the detailed report of the disassemblability analysis done in stage 3. By using the table, product designers can identify, for each component, which design attribute has a high numerical score. Meanwhile, Figure 6 shows that the lower cutter, upper cover, front part and coil have the potential to be improved. The lower cutter, upper cover and front part have low end-of-life value and high duration of disassembly time. On the contrary, the coil has high end-of-life value and high duration disassembly time. In order to increase the efficiency of disassembly process, those components should be disassembled very easily. It can be solved by changing the joining technique, redesigning the components or by repositioning them in the product hierarchy for easy disassembly.

Figure 5 Disassemblability report (see online version for colours)

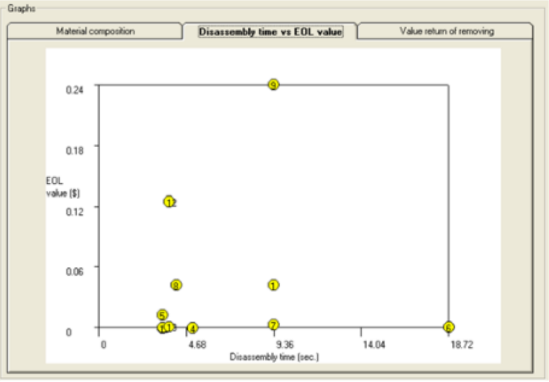


Task No	Task Name	Joint	Tool	Component	Comp. EOL val...	Subassembly No	Sub Ass. EOL ...	Force	Tools	Accessibility
1	Unscrew	Screw and bolt	Power screw di...	1	0.04158	Hair clipper	-0.02277	3	2	2
2	Pull	Snap fit	-	2	0.01232	SA1	-0.02385	0.5	1	2
3	Pull	Snap fit	-	3	0.00001	SA2	-0.02067	0.5	1	2
4	Unscrew	Screw and bolt	Power screw di...	4	0.00004	SA3	-0.02064	3	2	2
5	Pull	Snap fit	-	5	0.01232	SA4	-0.02052	0.5	1	2
6	Unscrew	Screw and bolt	-	6	0.00042	SA5	-0.02004	3	2	2
7	Unscrew	Screw and bolt	Power screw di...	7	0.00308	SA6	-0.01878	3	2	2
8	Pull	Snap fit	-	8	0.04158	SA7	-0.06	0.5	2	2

Recycling Rate = 80.1054%

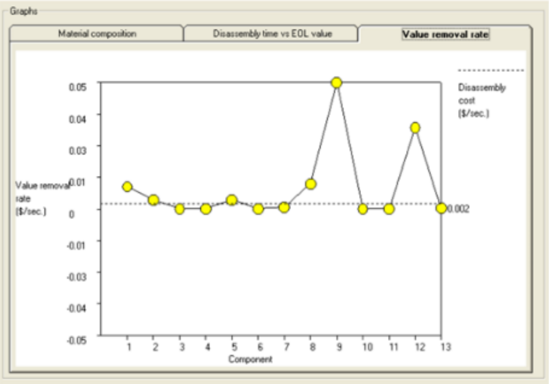
Disposal Rate = 19.8946%

Figure 6 End-of-life value vs. disassembly time (see online version for colours)



In Figure 7, the circles connected by the solid line represent value removal rate and the dashed line represents disassembly cost ($/s). Value removal rate is the ratio between end-of-life value ($) and disassembly time (s). Anything below the disassembly cost line (tip, handle, upper cover, front part, outer switch, inner switch and lower cover), is not economical to disassemble, while components plotted above this line (lower cutter, upper cutter, u-shape, magnet, coil and cable), can potentially make money if suitable quantities can be recovered. Note should be taken that, in this simple case study, the disassembly cost is assumed to be the labour cost (direct cost), while in the real world it is not only the labour cost acts as a driver of the disassembly cost but also other costs (indirect costs) such as maintenance, overhead and equipment depreciation cost.

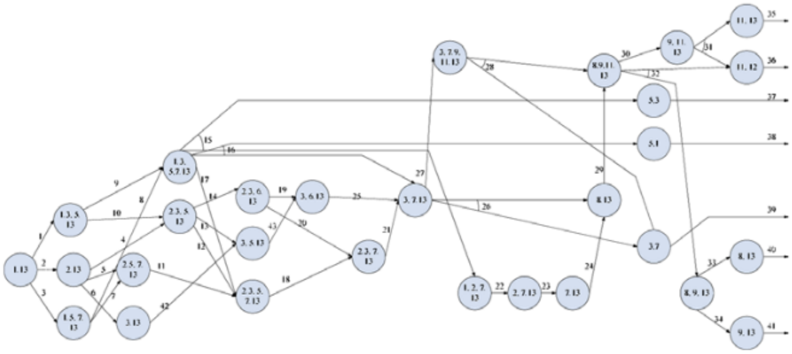
Figure 7 Value removal rate (see online version for colours)



Stage 6: Searching the optimum disassembly sequence

The first step in searching for the optimum disassembly sequence is developing the AND/OR graph, as shown in Figure 8. The nodes represent the subassemblies and the arcs represent the disassembly actions.

Figure 8 AND/OR graph of the hair clipper (see online version for colours)



In the nodes, the number 1/13 means consisting components 1, 2, 3, …, 13. List of the end-of-life value of the sub-assembly and the disassembly cost for each disassembly operation is shown in Table 5.

The revenue vector, cost vector and the transition matrix of this disassembly problem are shown in equations (14), (15) and in Table 6.

$$c = [0.01008 \quad 0.01872 \quad \dots \quad 0.00684] \tag{14}$$

$$r = [-0.01366 \quad -0.01359 \quad \dots \quad 0.0009]. \tag{15}$$

The cost vector represents the disassembly costs required to disengage the components [illegible] sub-assemblies from the hair clipper while the revenue vector represents the end-of-life value of the components or subassemblies. The total number of the possible sub-assemblies and disassembly tasks for this case study are 43 and 42. So, the size of the cost vector, revenue vector and transition matrix are 1 × 43, 1 × 42 and 42 × 43, respectively.

Table 5 Disassembly cost and sub-assembly revenue

Action	*Cost* ($)	*Action*	*Cost* ($)	*Subassembly*	*Revenue* ($)	*Subassembly*	*Revenue* ($)
1	0.1008	23	0.0684	1/13	–0.013662	1,5	0.0539
2	0.1872	24	0.1872	1/3,5/13	–0.01359	3,5	–0.000306
3	0.3744	25	0.3744	2/13	–0.01269	3,7	–0.00009
4	0.1008	26	0.1872	1/5,7/13	–0.012906	11,13	–0.001764
5	0.3744	27	0.0684	2/3,5/13	–0.012618	11,12	–0.00504
6	0.0684	28	0.1872	2/5,7/13	–0.011934	8,13	–0.002592
7	0.1872	29	0.0684	3/13	–0.012402	9,13	–0.007164
8	0.1008	30	0.0828	1/3,5,7/13	–0.012834	1	0.04158
9	0.1008	31	0.1872	2,3,6/13	–0.01233	2	0.01232
10	0.1872	32	0.1872	3,5/13	–0.01233	3	0.00001
11	0.1008	33	0.1872	2,3,5,7/13	–0.011862	4	0.00004
12	0.3744	34	0.0828	3,6/13	–0.012042	5	0.01232
13	0.0684	35	0.0684	2,3,7/13	–0.011574	6	0.00042
14	0.0684	36	0.0756	1,2,7/13	–0.012528	7	0.00308
15	0.1368	37	0	3,7/13	–0.011286	8	0.04158
16	0.2556	38	0	3,7/9,11/13	–0.01125	9	0.23716
17	0.1872	39	0.0684	8/13	–0.011196	10	0.00002
18	0.0684	40	0.0828	2,7/13	–0.011556	11	0.00008
19	0.0684	41	0.1872	7/13	–0.011268	12	0.1232
20	0.3744	42	0.0684	8,9,11/13	–0.01116	13	0.0009
21	0.0684	43	0.0684	9,11/13	–0.010188	–	–
22	0.1872	–	–	8,9,13	–0.008136	–	–

By applying the formula in equations (11)–(13), linear programming model for the hair clipper disassembly problem is as follow:

$$\text{Max } Z = \begin{bmatrix} -0.01 & 0.02383 & -0.0363 & \dots & 0.00577 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \dots \\ x_{43} \end{bmatrix} \tag{16}$$

subject to

$$\begin{bmatrix} -1 & -1 & -1 & \dots & 0 \\ 1 & 0 & 0 & \dots & 0 \\ 0 & 1 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \dots \\ x_{43} \end{bmatrix} \geq \begin{bmatrix} 0 \\ 0 \\ 0 \\ \dots \\ 0 \end{bmatrix} \tag{17}$$

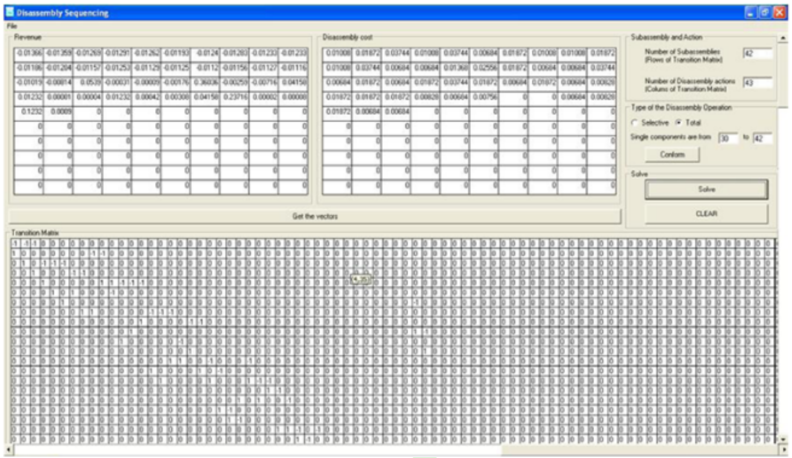
$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \dots \\ x_{43} \end{bmatrix} = \{0 \text{ or } 1\}. \tag{18}$$

Table 6 Transition matrix

	Disassembly action																																										
Subassembly	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
1,2,3,4,5,6,7,8,9,10,11,12,13	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1,2,3, 5,6,7,8,9,10,11,12,13	1	0	0	0	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,3,4,5,6,7,8,9,10,11,12,13	0	1	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1,2,3,4,5,7,8,9,10,11,12,13	0	0	1	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,3,,5,6,7,8,9,10,11,12,13	0	0	0	1	0	0	0	0	0	1	1	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,3,4,5, 7,8,9,10,11,12,13	0	0	0	0	1	0	1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3,4,5,6,7,8,9,10,11,12,13	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
1,2,3,5,7,8,9,10,11,12,13	0	0	0	0	0	0	0	1	1	0	0	0	0	0	-1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2,3, 6,7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3, 5,6,7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1
2,3, 5, 7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3, 6,7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
,2,3, 7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	-1	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1,2, 7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3, 7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3, 7,8,9, 11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8, 9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2, 7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7,8,9,10,11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8,9, 11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0
9, 11,12,13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	0	0	0	0	0	0	0	0	0	0
8,9, 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	-1	0	0	0	0	0	0	0	0	0
1, 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
3, 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0
3, 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
11, 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	-1	0	0	0	0	0	0	0	0
9, 12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	-1	0	0	0	0	0	0	0
8, 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0	0
9, 13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	-1	0	0
1	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
2	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
4	1	0	0	1	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1
6	0	0	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	0	0

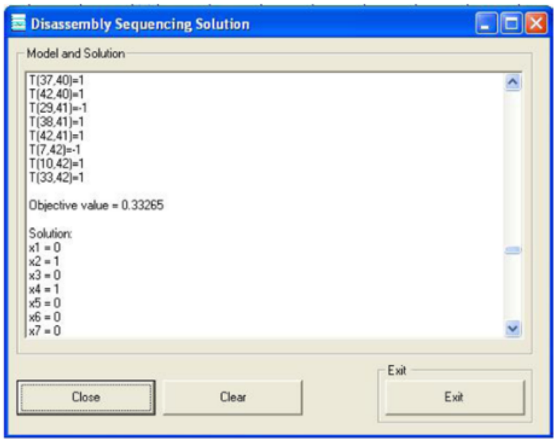
The template for searching the optimum disassembly sequence is shown in Figure 9 and the result is shown in Figure 10.

Figure 9 Template for searching for the optimum disassembly sequence (see online version for colours)



Number of Subassemblies (Rows of Transition Matrix) 42
Number of Disassembly actions (Colums of Transition Matrix) 43
○ Selective ● Total
Single components are from 30 to 42

Figure 10 Optimum disassembly sequence report (see online version for colours)



```
T(37,40)=1
T(42,40)=1
T(29,41)=-1
T(38,41)=1
T(42,41)=1
T(7,42)=-1
T(10,42)=1
T(33,42)=1

Objective value = 0.33265

Solution:
x1 = 0
x2 = 1
x3 = 0
x4 = 1
x5 = 0
x6 = 0
x7 = 0
```

The developed software has the ability to find the optimum sequence for the selective and total disassembly operations. For the selective disassembly sequence, the optimum sequences is 1-9-15-22-23-24-29-32-34-37-41 producing profit $Z = \$0.63396$ and for the total disassembly sequence, the optimum sequence is 2-4-12-18-21-26-29-30-31-35-36-39, yielding a profit $Z = \$0.33265$.

Based on the result of the case study, some redesign alternatives are suggested for improving the end-of-life performance of the hair clipper. According to Figure 6, the coil and upper cover have the potential to be improved. The scenario for redesign is to reduce the number of screws of these two components. In the current design, the upper cover has four screws; it can be reduced into two screws. The coil has two screws; this can be reduced into a single screw. By applying this, the disassembly time of the upper cover and coil will be reduced to 9.36 and 4.68 second. Table 7 shows the disassemblability evaluation for redesigning the lower cutter. It will also reduce the disassembly cost of the upper cover and coil to $0.01872 and $0.00936, respectively. The disassembly times of these two components are estimated by using the disassemblability evaluation template of the developed software, as shown in Figure 3. The optimum disassembly sequences of the redesigned hair clipper are the same as the sequence before redesign is done for both, selective and total disassembly, respectively but it yields a higher profit, $0.64332 and $0.34957, respectively. Table 8 summarises the result of the redesign.

Table 7 Disassemblability evaluation of the redesigned upper cover

Design attribute	*Design attribute/parameter*	*Score*
Force	Push with hand	1
Material handling	Component dimensions	2
	Magnitude of weight	2
	Symmetric components are easy to handle	0.8
Requirement of tools	Exertion of force	1
Accessibility	Dimensions/length, breadth, depth, radius, angle made with surface	1
	Location/on plane surface	1
Positioning	Symmetry	1.2
Total		*10*

Disassembly time = Total × 10 × 0.036 = 10 × 10 × 0.036 = 3.6 s

Disassembly cost = Disassembly time (s) × Labour cost ($/s) = 3.6 × 0.00005 = $0.00018

Table 8 Redesign result

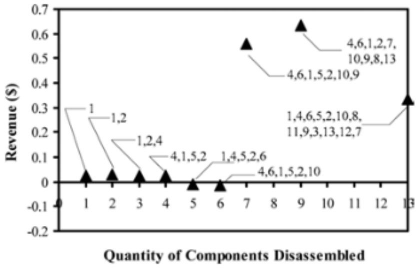
	Current design			*Redesign*		
		Disassembly revenue			*Disassembly revenue*	
Comp.	*Disassembly time*	*Selective*	*Total*	*Disassembly time*	*Selective*	*Total*
Coil	18.72 s	$0.63396	$0.33265	9.36 s	$0.64332	$0.34957

6 Sensitivity analysis

In most practical applications, problem data are known exactly and are often estimated as best as possible. It is, therefore, important to study the effect on the profit gained from disassembly and recycling activities to variations in certain data. In this work, the effect of the quantity of components disassembled and the percentage of the material extracted to the current solution will be explored. Figure 11 shows the change on revenue to the variation of the number of components disengaged. It shows that disengage components

4, 5, 6 and 10, together with components 1 and 2, will decrease the revenue gained. This is because components 3, 4, 6 and 10, which have a value of removal rate lower than the disassembly cost. Although components 1, 2, and 5 have value removal rate higher than the disassembly cost but it cannot compensate for the negative revenue accumulated by components 4, 6, and 10. If it is decided to continue the disassembly process, by disassembling component number 10 or 9, the revenue will increase enormously. This is because of component 9 which has the highest value of removing rate. But if it is decided to totally disassemble the product, the revenue gained will decrease because components 10, 11 and 13 are not economical to disassemble.

Figure 11 Revenue as the function of quantity of components disassembled



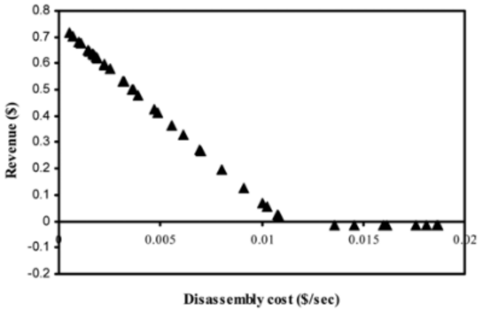
From Table 9, it can be concluded that by increasing the share of polymer to be disassembled from the product the revenue will be decreased. Increase in the revenue from 0.559260 to 0.633972 is not caused by the increase of polymer extracted from the product (6.32–18.18%) but it is caused by the decision to disassemble 7.11% metal without alloy coming from component 8.

Table 9 Effect of the share of material extracted to the revenue gained

Revenue ($)				*Material released* (%)		
Before redesign	*After redesign*	*Feasible sequence*	*Component released*	*Metal with alloy*	*Metal without alloy*	*Polymer*
0.023832	0.037494	2	1	7.11	0.00	0.00
0.029600	0.043262	2,6	1,2	9.22	0.00	0.00
0.022872	0.036534	2,6,42	1,2,4	9.22	0.00	0.53
0.025399	0.039062	1,10,14,19	4,1,5,2	11.33	0.00	0.53
–0.011332	0.021050	2,4,14,19,25	1,4,5,2,6	11.33	0.00	6.06
–0.016462	–0.016462	1,9,17,18,21,27, 28,32	4,6,1,5,2,10	11.33	0.00	6.32
0.559260	0.582282	1,9,17,18,21,27, 28,32,33	4,6,1,5,2,10,9	51.91	0.00	6.32
0.633972	0.602778	1,9,15,22,23,24, 29,32,33,40	4,6,1,2,7,10,9,8, 13	50.33	7.11	18.18
0.33265	0.365024	2,4,12,18,21,26, 29,30,31,35,36, 39	1,4,6,5,2,10,8,11, 9,3,13,12,7	73.52	7.11	19.37

In disassembly problem, the disassembly cost also has an effect on the selection of the optimum disassembly sequence. Figure 12 shows that the solution of the model suggests to not disassemble the hair clipper if the labour cost is higher than 0.0135 $/s. Otherwise, the recycling and reuse value of the material can compensate the cost of disassembly process.

Figure 12 Revenue as the function of disassembly cost



7 Discussion

The main outcome of this work is the methodology developed to aid product designers to analyse the disassemblability and recyclability of end-of-life products. The methodology was also converted into a computer software and expected can deliver a dynamic characteristic in order to comply the change in legislation, cost and technology.

In general, there are two main attributes required to be considered in treating the end-of-life products, cost attributes and environmental attributes. The cost attributes are expenditure required to take back, disassembly and reprocess the end-of-life product. Meanwhile, the environmental attributes address the global requirements and issues such as recycling target decided by the government in the legislation. The main contribution of this work is to provide a methodology or tool to compromise the trade-off of these two attributes.

This work integrated the three important aspects of the disassemblability and recyclability analysis of end-of-life products in one framework. These aspects are end-of-life option determination, disassemblability and recyclability analysis, and disassembly sequence. These aspects need to be analysed to comply with the requirements of the legislation to take back and recycle the end-of-life products and the cost incurred for taking back, disassembling and reprocessing the end-of-life products.

The end-of-life option determination will guide the designer to choose the appropriate end-of-life option of the product. The end-of-life value calculation will show the value which can be achieved from the appropriate end-of-life option decided for the components. The disassemblability evaluation will aid the designers in reducing the difficulty for disassembly, disassembly time and disassembly cost required. The recyclability analysis will show whether the design meets or does not meet the legislation at feasible expenditure in terms of recycling target. The search for the optimum disassembly sequence will minimise the disassembly cost and maximise the end-of-life value and, finally, increase the profitability which can be achieved from the end-of-life treatment.

Integrating the end-of-life concept into the early design of product is one of important aspects that need to be considered in decreasing impact of end-of-life products to the environment. The choice of product concept, structure, material and process during design stages has consequences for the environment during the entire life cycle of the product. It is essential to integrate recycling criteria into all phases of the product development process in order to ensure the design of an environmentally compatible product, optimised for recycling (BMW Group, 2002). The proposed software was developed specially to assist product designers to evaluate product design with respect to legislation, recycling and economic value. It also can be used to explore the 'what if' scenario that can possibly exist due to the design that is being developed in order to fulfil the legislation and ensure that it is achieved at feasible expenditure.

In order to verify and validate the developed software, an end-of-life product was introduced with the intention to investigate the appropriate end-of-life option for its components, disassemblability, suitability for recycling, recyclability and optimum disassembly sequence.

8 Conclusion

EDAS, a software to analyse the disassemblability and recyclability of the end-of-life product, is presented here. It consists of three elements, end-of-life option determination, numerical evaluation of disassemblability and searching for an optimum disassembly sequence. This software can be used by product designers and manufacturers to evaluate the disassemblability of their design, asses the suitability of recycling and check the recyclability. It will aid product designers and manufacturers to know which materials in their product may be recycled at feasible and reasonable expenditure. For the recycling and dismantling companies, the ability of the software to search for the optimum disassembly sequence will be beneficial to them in reducing the disassembly cost of the end-of-life products.

For further research, Multi-Criteria Decision Analysis (MCDA) can be integrated into the methodology or software to select the appropriate end-of-life option of the product's components because the selection of the end-of-life option is also subject to the law, economic, environmental, and social factors.

References

BMW Group (2002) *Manual for Recycling-Optimized Product Development*, BMW Group, Germany.

Desai, A. (2002) *A Design for Disassembly Algorithm Based on Quantitative Analysis of Design Parameters Affecting Disassemblability*, Master Thesis, University of Cincinnati, USA.

Desai, A. and Mital, A. (2005) 'Incorporating work factors in design for disassembly in product design', *Journal of Manufacturing Technology Management*, Vol. 16, No. 7, pp.712–732.

Dong, T., Zhang, L., Tong, R. and Dong, J. (2006) 'A hierarchical approach to disassembly sequence planning for mechanical product', *International Journal of Advanced Manufacturing Technology*, Vol. 30, Nos. 5–6, pp.507–520.

EPA (2008) *Statistics on the Management of Used and End-of-Life Electronics*, Website [URL]: http://www.epa.gov/epawaste/conserve/materials/ecycling/manage.htm

Kongar, E. and Gupta, S.M. (2006) 'Disassembly sequencing using genetic algorithm', *International Journal of Advanced Manufacturing Technology*, Vol. 30, Nos. 5–6, pp.497–506.

Lambert, A.J.D. (1999) 'Linear programming in disassembly/clustering sequence generation', *Computers and Industrial Engineering*, Vol. 36, No. 4, pp.723–738.

Lambert, A.J.D. and Gupta, S.M. (2005) *Disassembly Modeling for Assembly, Maintenance, Reuse and Recycling*, CRC Press, Boca Raton, USA.

Lee, S.G., Lye, S.W. and Khoo, M.K. (2001) 'A multi-objective methodology for evaluating product end-of-life options and disassembly', *International Journal of Advanced Manufacturing Technology*, Vol. 18, No. 2, pp.148–156.

Lye, S.W., Lee, S.G. and Khoo, M.K. (2002) 'ECoDE – an environmental component design evaluation tool', *Engineering with Computers*, Vol. 18, No. 1, pp.14–23.

Mascle, C. and Balasoiu, B.A. (2003) 'Algorithmic selection of a disassembly sequence of a component by a wave propagation method', *Robotics and Computer-Integrated Manufacturing*, Vol. 19, No. 5, pp.439–448.

Rose, C.M. and Stevels, A. (2001) 'Metrics for end-of-life strategies (ELSEIM)', *IEEE International Symposium on Electronics and the Environment*, 7–9 May 2001, Denver, CA, pp.100–105.

Shan, H., Li, S., Huang, J., Gao, Z. and Li, W. (2007) 'Ant colony optimization algorithm-based disassembly sequence planning', Paper Presented at the *2007 IEEE International Conference on Mechatronics and Automation*, 5–8 August 2007, Harbin, China, pp.867–872.

The European Parliament and of the Council of European Union (2000) *Directive 2000/53/Ec of the European Parliament and of the Council of 18 September2000 on End-of-life Vehicles*, Official Journal of the European Communities, Brussels.

Yi, H.C., Park, Y.C. and Lee, K.S. (2003) 'A study on the method of disassembly time evaluation of a product using work factor method', Paper Presented at the *IEEE International Conference on Systems, Man and Cybernetics*, 5–8 October 2003, Washington DC, USA, pp.1753–1759.

EDAS

ORIGINALITY REPORT

21%	13%	18%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	S.G. Lee, S.W. Lye, M.K. Khoo. "A Multi-Objective Methodology for Evaluating Product End-of-Life Options and Disassembly", The International Journal of Advanced Manufacturing Technology, 2001 Publication	4%
2	etd.ohiolink.edu Internet Source	2%
3	hdl.handle.net Internet Source	1%
4	web.ornl.gov Internet Source	1%
5	Go, T.F.. "Disassemblability of end-of-life vehicle: a critical review of evaluation methods", Journal of Cleaner Production, 201109 Publication	1%
6	www.medifastpeoriaaz.com Internet Source	1%
7	ccsenet.org	

	Internet Source	1 %
8	C. Herrmann, A. Frad, T. Luger, F.-L. Krause, Z. Ragan. "Integrating End-of-Life Evaluation in Conceptual Design", Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment, 2006., 2006 Publication	1 %
9	Muhamad Zameri Mat Saman. "Design for End-of-Life Value Framework for Vehicles Design and Development Process", Journal of Sustainable Development, 02/28/2012 Publication	1 %
10	A.J.D. Lambert. "Linear programming in disassembly/clustering sequence generation", Computers & Industrial Engineering, 1999 Publication	1 %
11	core.ac.uk Internet Source	1 %
12	www.wuperbooks.org Internet Source	<1 %
13	(Fred) Lambert, . "Disassembly Network Features", Resource Management, 2004. Publication	<1 %
14	Christian Mascle. "A liaison model for disassembly-reassembly product ecodesign",	<1 %

	International Journal of Design Engineering, 2009 Publication	
15	mml.stanford.edu Internet Source	<1%
16	link.springer.com Internet Source	<1%
17	Cui hua Zhang. "Quality control strategy in supply chain under asymmetric information", International Journal of Operational Research, 2009 Publication	<1%
18	Anil Mital. "Enhancing the product development process through a sequential approach. Part II: assembly and disassembly", International Journal of Product Development, 2007 Publication	<1%
19	Go, T.F.. "Genetically optimised disassembly sequence for automotive component reuse", Expert Systems With Applications, 201204 Publication	<1%
20	Ullah, Aleem, Muhamad Zameri Mat Saman, and Salwa Mahmood. "Development of Multi-Criteria Decision Analysis Methodology to Determine Product End-of-Life Treatment Options", Advanced Materials Research, 2013. Publication	<1%

21	Tobias Zettier, Marcus Essenpreis, Klaus Vornberger. "Evaluation of the Recyclability of Vehicles During the Product Development Phases", SAE International, 2000 Publication	<1 %
22	A MITAL. "Designing for Assembly and Disassembly", Product Development, 2008 Publication	<1 %
23	C Lu. "A multi-objective disassembly planning approach with ant colony optimization algorithm", Proceedings of the Institution of Mechanical Engineers Part B Journal of Engineering Manufacture, 11/01/2008 Publication	<1 %
24	Devdas Shetty, Ahad Ali. "A new design tool for DFA/DFD based on rating factors", Assembly Automation, 2015 Publication	<1 %
25	Malin Tarrar, Mélanie Despeisse, Björn Johansson. "Driving vehicle dismantling forward - A combined literature and empirical study", Journal of Cleaner Production, 2021 Publication	<1 %
26	"Design for Innovative Value Towards a Sustainable Society", Springer Science and Business Media LLC, 2012 Publication	<1 %

27	Anoop Desai, Anil Mital. "Evaluation of disassemblability to enable design for disassembly in mass production", International Journal of Industrial Ergonomics, 2003 Publication	<1 %
28	R. Caudill. "Disassembly modeling, planning and application: a review", Proceedings 2000 ICRA Millennium Conference IEEE International Conference on Robotics and Automation Symposia Proceedings (Cat No 00CH37065) ROBOT-00, 2000 Publication	<1 %
29	Zhao, Na, Rui Mu, and Wen Wu Wang. "Disassembly Evaluation Based on Principal Component Analysis", Advanced Materials Research, 2013. Publication	<1 %
30	www.ecyclebest.com Internet Source	<1 %
31	www.mdpi.com Internet Source	<1 %
32	"Ontology-based semantic integration scheme for medical image grid", International Journal of Grid and Utility Computing, 2009 Publication	<1 %

33	Lily Amelia, D.A. Wahab, A.R. Ismail, C.H. Che Haron. "Disassembly time evaluation for enhancing the reusability of automotive components", 2009 IEEE International Conference on Industrial Engineering and Engineering Management, 2009 Publication	<1 %
34	M.M. Youssif, R.A. Alkadeem, M.A. El Dardiry. "Incorporating ergonomic factors in disassembly sequence planning", Alexandria Engineering Journal, 2011 Publication	<1 %
35	S. Harivardhini, Amaresh Chakrabarti. "A new model for estimating End-of-Life disassembly effort during early stages of product design", Clean Technologies and Environmental Policy, 2016 Publication	<1 %
36	Wenyuan Wang. "Design for sustainable manufacturing: applying modular design methodology to manage product end-of-life strategy", International Journal of Product Lifecycle Management, 2011 Publication	<1 %
37	Lambert, A.J.D.. "Optimizing disassembly processes subjected to sequence-dependent cost", Computers and Operations Research, 200702	<1 %

Publication

38	dias.library.tuc.gr Internet Source	<1 %
39	fr.scribd.com Internet Source	<1 %
40	www.inderscienceonline.com Internet Source	<1 %
41	www.tandfonline.com Internet Source	<1 %
42	"Evaluation of a ramp cavity based concept supersonic combustor using CFD", Progress in Computational Fluid Dynamics An International Journal, 2009 Publication	<1 %
43	T.F. Go, D.A. Wahab, M.N. Ab. Rahman, R. Ramli. "A Design Framework for End-of-Life Vehicles Recovery: Optimization of Disassembly Sequence Using Genetic Algorithms", American Journal of Environmental Sciences, 2010 Publication	<1 %
44	T.F. Go, D.A. Wahab, M.N.Ab. Rahman, R. Ramli, C.H. Azhari. "Disassemblability of end-of-life vehicle: a critical review of evaluation methods", Journal of Cleaner Production, 2011 Publication	<1 %

45	Wenyuan Wang, Mitchell M. Tseng. "Chapter 22 Life Cycle Commonality: As a Systematic Approach to Achieve Product Design for Sustainability", Springer Science and Business Media LLC, 2010 Publication	<1 %
46	Xiaoying Zhou. "chapter 5 Sustainable Electronic Product Design", IGI Global, 2009 Publication	<1 %
47	mafiadoc.com Internet Source	<1 %
48	publications.polymtl.ca Internet Source	<1 %
49	scholarbank.nus.edu.sg Internet Source	<1 %
50	studentsrepo.um.edu.my Internet Source	<1 %
51	www.ideals.illinois.edu Internet Source	<1 %
52	"A Bayesian learning of probabilistic relations between perceptual attributes and technical characteristics of car dashboards to construct a perceptual evaluation model", International Journal of Product Development, 2009 Publication	<1 %

53	"Re-engineering Manufacturing for Sustainability", Springer Science and Business Media LLC, 2013 Publication	<1 %
54	portal.research.lu.se Internet Source	<1 %
55	"Design for Innovative Value Towards a Sustainable Society", Springer Nature, 2012 Publication	<1 %
56	Paul Vanegas, Jef R. Peeters, Dirk Cattrysse, Paolo Tecchio, Fulvio Ardente, Fabrice Mathieux, Wim Dewulf, Joost R. Duflou. "Ease of disassembly of products to support circular economy strategies", Resources, Conservation and Recycling, 2018 Publication	<1 %

Exclude quotes	On	Exclude matches	Off
Exclude bibliography	On		