A technical and economic model for end-of-life (EOL) options of industrial products

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Abstract: In the field of sustainable manufacturing, many research efforts have been focused on the redesign of products towards improved disassemblability and recyclability. However, recycling as an end-of-life (EOL) option is only the first step towards sustainable manufacturing. A more efficient strategy is the reuse of the components, sub-assemblies or entire products. The decision between using an old component or producing a new component depends on a variety of parameters with many uncertainties.

This paper presents a decision making model, integrating technical, economic and environmental considerations for the product's evaluation. The model uses new parameters such as the product value, representing the technical status of a component, or the environmental value, representing the life cycle impact of a component. The model is used for comparing the values of a new component with an old component, thus supporting the decision between reuse, remanufacture or disposal. Furthermore, the model can be used to investigate redesign suggestions.

Keywords: Sustainable manufacturing; reuse; recycling; decision making model.

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1 Introduction

Since sustainable manufacturing has become a challenging global issue in the manufacturing area, a wide range of research has been carried out to deal with the more effective use of natural resources and the reduction of environmental impacts during the product life cycle, while still meeting customer's demands for high quality and affordable products. A closed loop manufacturing system has been proposed to prolong the product life cycle and to restrain the flow of material and energy. Several methods, such as Design for Environment (DfE), Design for Disassembly (DfD), and Design for Recycling (DfR), have been developed and dedicated to increase disassemblability and recyclability of a product.

However, recycling as an end-of-life (EOL) option is only the first step towards sustainable manufacturing. A more efficient strategy is the reuse of components, sub-assemblies or entire products. Although it is admitted that reuse is the ultimate way of increasing the sustainability [1-6], in reality it is not easy to apply. Many uncertainties influence the decision towards reuse of a component or a product. The most common problem regarding the reuse strategy is the uncertainty of the product's quality after use, since it is not acceptable to sell or use a product the quality of which is not assured [4].

The other problem is that the implementation of a closed loop system for product development and manufacturing for products that were not designed for reuse purposes is costly and inefficient in terms of technology and investment. For example, the disassembly process is very time consuming and costly, unless the product was designed for disassembly. Likewise, the take-back and collection process for used products needs structured distribution channels, otherwise it is also a potential trigger for increasing costs. Consequently, many uncertainties cause the decision making process to become more difficult and complex. Therefore, before applying reuse as a strategy, all factors have to be considered comprehensively in order to avoid wrong decisions and costly solutions.

Considering the superior benefits of reuse and also the impediments mentioned above, this paper presents a decision making model, integrating technical, economic and environmental considerations for the product's evaluation.

2 A decision making model

Traditionally, decision making models used by manufacturers employ a set of criteria to assess the product's performance. These criteria are usually based on the interest of the manufacturers, for instance minimising cost, maximising profit, or optimising the utilisation of resources. However, for a comprehensive approach, not only do the interests of manufacturers need to be considered but also the interests of customers. Also the environmental impact has to be included [7]. The model presented in this paper takes these interests into account by addressing both the manufacturers' interests as well as focusing on providing satisfactory service for customers without causing any serious problems to the environment.

2.1 The concept

Literature shows that many researchers have focused on economics and the environment as the main drivers for adopting end-of-life strategies [8,9]. Other studies concentrated on customer satisfaction as the main driver through quality aspects [2-4]. The proposed model brings all three factors into the decision making process to evaluate the EOL of a component.

In addition, for a comprehensive decision making process all phases of the product life cycle have to be considered [1,8-10]. The phases for new and used components are slightly different. In the model, the phases for a new product are material phase, manufacturing phase, usage phase and end-of-life phase. For a reused product the phases are procurement phase, remanufacturing phase, usage phase, and end-of-life phase (Figure 1). The procurement phase covers the activities of collection and transportation of used products. The remanufacturing phase covers all activities for recovering and re-working of used components to restore them to a 'like-new' condition [5]. 'Like-new' condition implies that an old component will perform as good as a new one. Consequently, if the performances of an old and a new component are equal, their technical and environmental costs during usage and end-of-life phase are assumed to be equal (grey areas in Figure 1). Therefore these two phases have no influence on the decision process and they are not considered in the decision model.

The decision model is aimed at comparing the three EOL options, namely reuse, recycling of material and disposal, for an old and a new component. The model generates dollar values for both components.

2.2 The model structure

For the model, three new parameters have been defined, namely Product Gain (PG), Product Value (PVL), and Product Life Cycle Cost (PLCC).

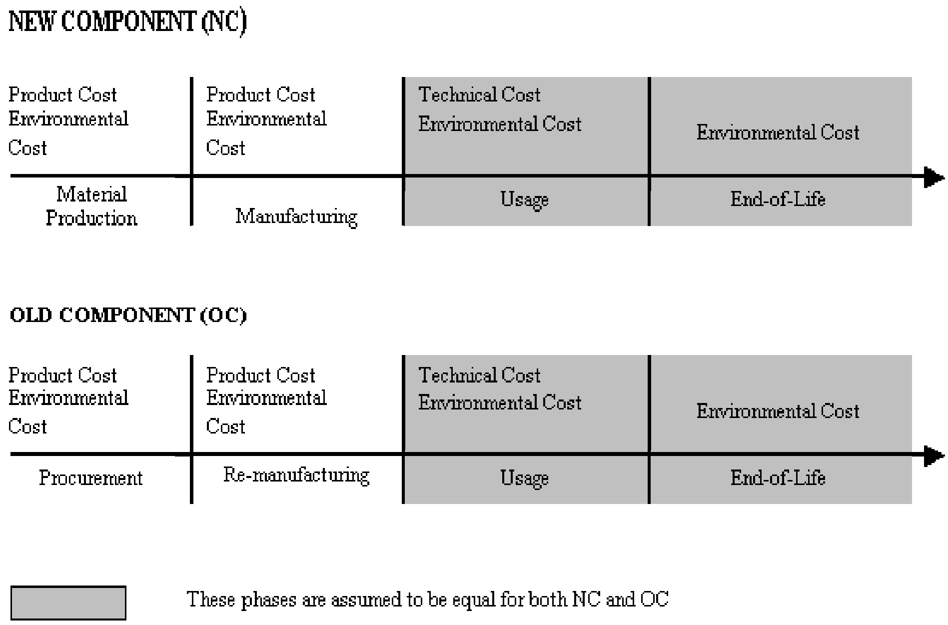
$$PG = PVL - PLCC \tag{1}$$

The Product Gain, (PG), represents the monetary outcome from the sales of the product after deducting product and environmental cost.

The Product Value, (PVL), represents the technical performance or quality status of the product, which can be measured by the Product Effectiveness (PE). For a new product the performance can be set to 100%, that means PE = 1. The dollar value is introduced by using the market prize MP as the multiplier.

$$PVL = MP \times PE \quad (2)$$

Figure 1 The life cycle phases and their associated costs for a new and a reused component



Product Effectiveness, (PE), is defined as to how effectively the product performs its intended function and meets customer requirements [11]. PE is a combination of Availability (A), Dependability (D), and Capability (C). It can be calculated as:

$$PE = A \times D \times C \quad (3)$$

where:

A = f(mean time to failure, mean time to replace)

D = f(mean time to failure, mean application time)

C = f(mean time to failure, mean application time, optimum product performance per unit time)

For example, if the product is a washing machine motor and the application is to rotate the spin bowl during the washing cycle, then PE measures the probability (P) of the motor finishing the whole washing cycle satisfactorily. In this case

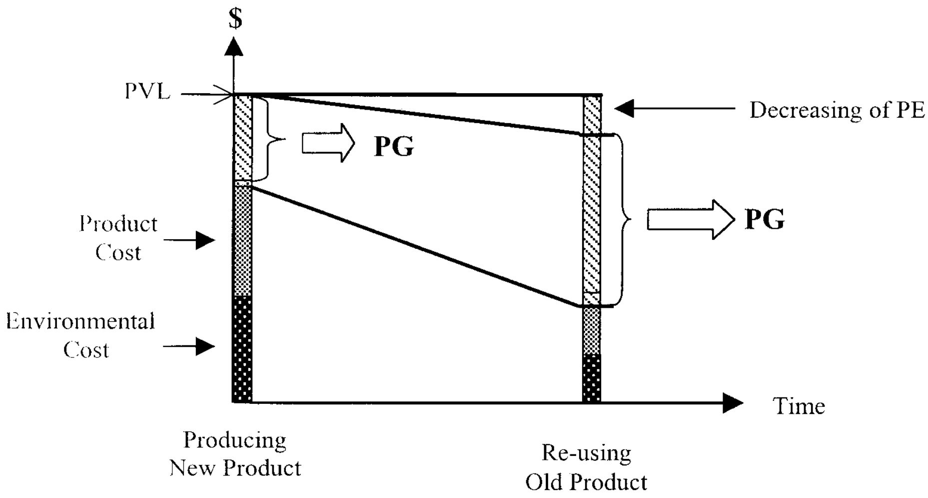
PE = P(Motor is available at the start of washing) x

P(Motor is dependable for the duration of the washing, given it is available) x

P(Motor provides satisfactory spin to dry clothes, given it is dependable).

The Product Effectiveness can decrease over time through the use of the product. Consequently, if a product is reused, its Product Value may be smaller than the PVL of the new product (Figure 2). Whether or not PVL decreases over time depends entirely on the type of the product or component. For instance a steel bracket in a copying machine will not decrease its PVL during proper use. However, a ball bearing will decrease its PVL although it can still be fully functional with a reduced remaining lifetime.

Figure 2 The effect of time on product performance



The third parameter, Product Life Cycle Cost PLCC, represents all costs that occur during the product's life cycle phases.

$$PLCC = C_P + C_E \quad (4)$$

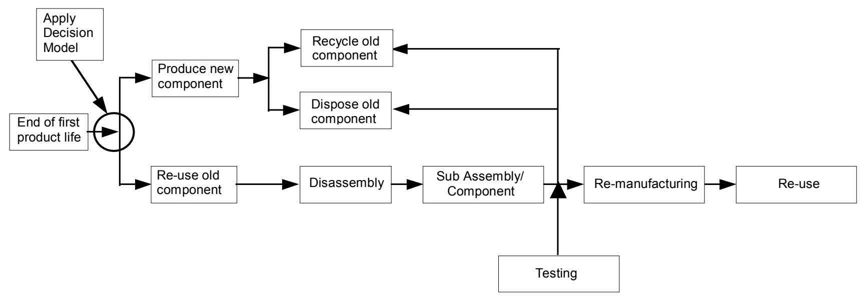
where:

C_P = Product cost

C_E = Environmental cost

The life cycle costs are different for each EOL option. The four options to be considered are new component, reuse, recycling or disposal of an old component (Figure 3). As mentioned earlier, for the purpose of cost comparison in this model, the life cycle phases of usage and end-of-life are assumed to be equal for a new and an old component. Therefore, they do not appear in the cost calculation.

Figure 3 End of life strategies



For a new component:

$$C_{Pnew} = C_{mat} + C_{man} + C_{op} \quad (5)$$

$$C_{Enew} = C_{Emat} + C_{Eman} \quad (6)$$

where:

C_{mat} = Material cost

C_{man} = Manufacturing cost (including processes, assembly, labour and overheads costs)

C_{op} = Operational cost (including administration, marketing and distribution)

C_{Emat} = Environmental cost for material phase

C_{Eman} = Environmental cost for manufacturing phase

For an old component:

In case of the reuse option:

$$C_{Preu} = C_{pro} + C_{rem} \quad (7)$$

$$C_{Ereu} = C_{Epro} + C_{Erem} \quad (8)$$

where:

C_{pro} = Procurement cost (including collection, take back, transport, and storage)

C_{rem} = Remanufacturing cost (including disassembly, cleaning, sorting, testing and reprocessing)

In case of the recycling option:

$$C_{Prec} = C_{pro} + C_{rec} - R_{rec} \quad (9)$$

$$C_{Erec} = C_{Epro} + C_{Erec} \quad (10)$$

where:

R_{rec} = Revenue as a result of material recycling

In case of the disposal option:

$$C_{Pdis} = C_{pro} + C_{dis} \quad (11)$$

$$C_{Edis} = C_{Epro} + C_{Edis} \quad (12)$$

where:

C_{dis} = Disposal cost

2.3 The decision making model

Figure 4 illustrates a flowchart of the decision making model. It shows that PG has to be calculated for each alternative option, i.e. reusing an old component or producing a new one. Then a comparison is carried out. If PG for producing a new component is higher than that for reusing an old component, the first alternative will be selected as the best choice. Then the old component will go to the next analysis to decide whether it will be recycled or disposed. This analysis is based on the value of PLCC since there is no remaining technical value in the component.

If the product gain is negative or zero for both the new and the old component, it indicates that the component should not be manufactured due to environmental costs. In this situation, a redesign of the component is suggested towards a more environmentally friendly design, and the old components are evaluated for recycling. This decision making model should be applied at the beginning of the decision process as shown in Figure 3. By applying the model in the early stages of the decision process, costly disassembly operations might be avoided.

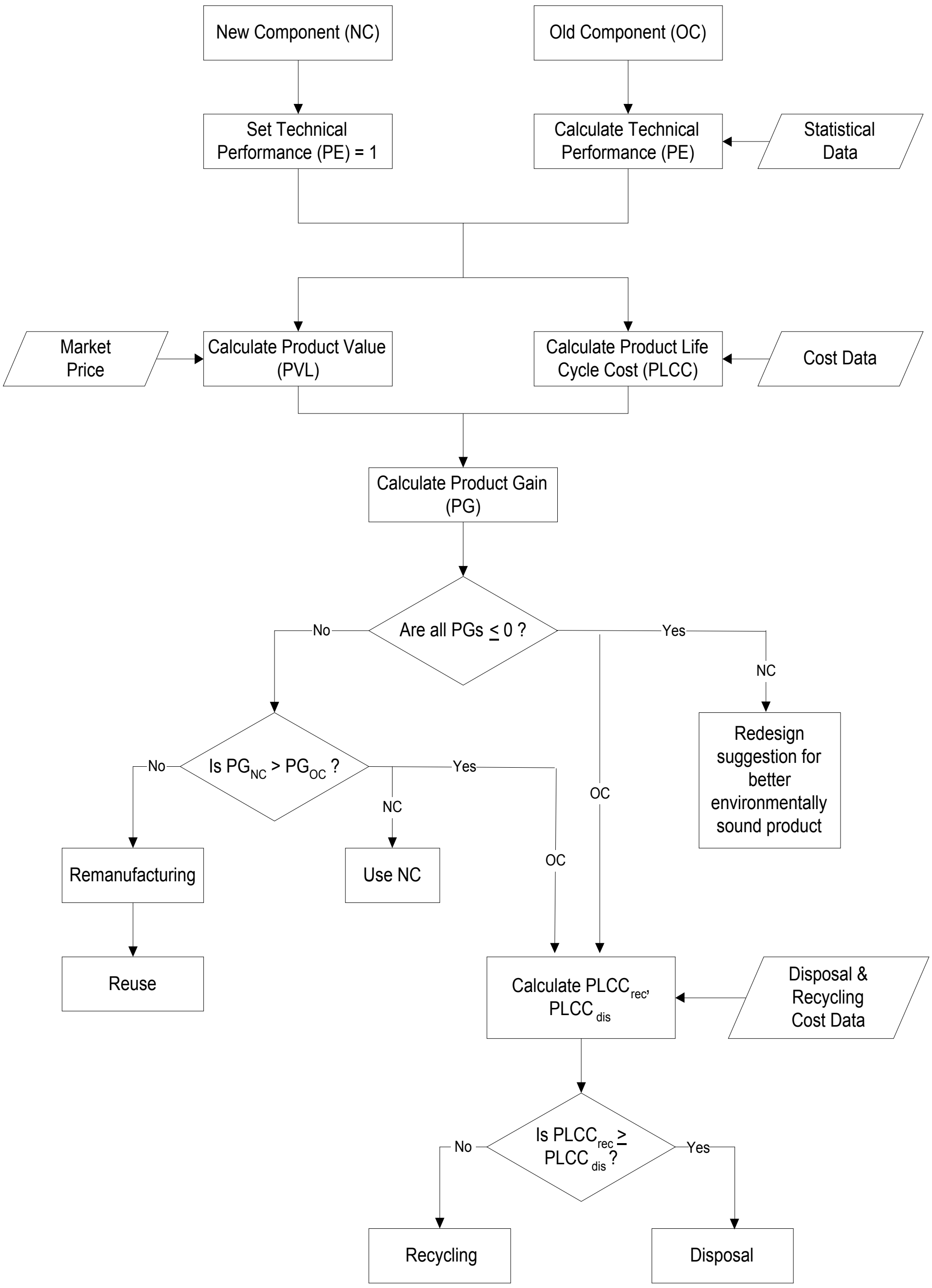
3 A case study

As part of an ongoing project on recycling of appliances, a toaster has been selected to demonstrate the application of the model. The toaster used for the case study is a ‘two sliced’ pop-up toaster, which operates at 230-240 volts and 800 watts power. The toaster’s parts and their EOL options are listed in Table 1.

Table 1 The toaster parts

Part Name	*Material*	*Market Price*	*Required Remanufacturing Processes*
Base	Steel	$8	- Cleaning - Coating
Electrical Cord	- Plastic - Copper	$1	Cutting
Casing	Aluminium	$3	- Cleaning - Coating
Mechanical Lift	Steel	$10	Light Machining
Halogen Tubes	- Halogen - Glass	$12	-
Electronic Components	Silicone	$6	-

Figure 4 Flowchart of the decision making model



3.1 Production flow

To produce a new toaster, the company manufactures the casing, base, and mechanical lift in-house, while the other parts, the electrical cord, halogen tubes, and electronic components, are purchased from suppliers. The parts are then assembled to a toaster (Figure 5). Producing a new toaster with some remanufactured parts requires a different production flow, which is shown in Figure 6. It is assumed that the potentially reusable parts could be obtained in the required high quality condition at the end of their first life, so that they could be used in the second lifetime. Therefore, the company only purchases new halogen tubes and electronic components from suppliers.

Figure 5 Production flow for producing a new toaster

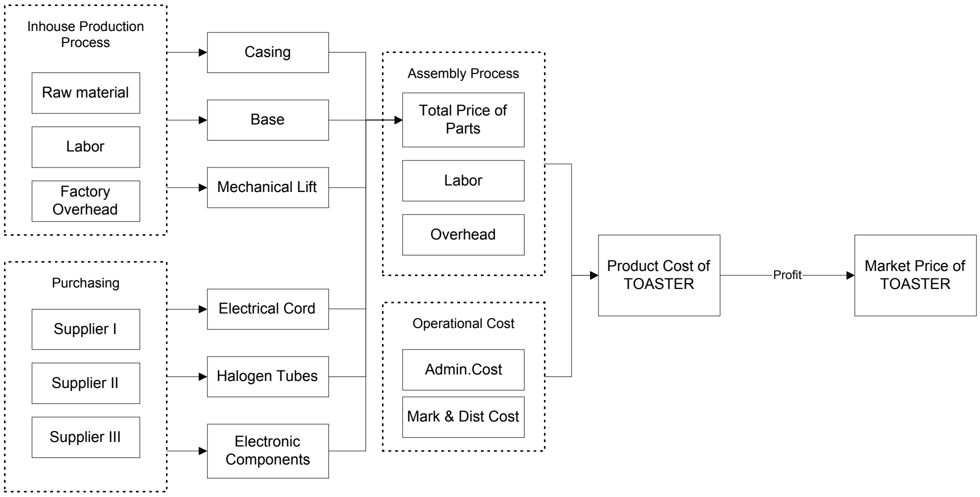
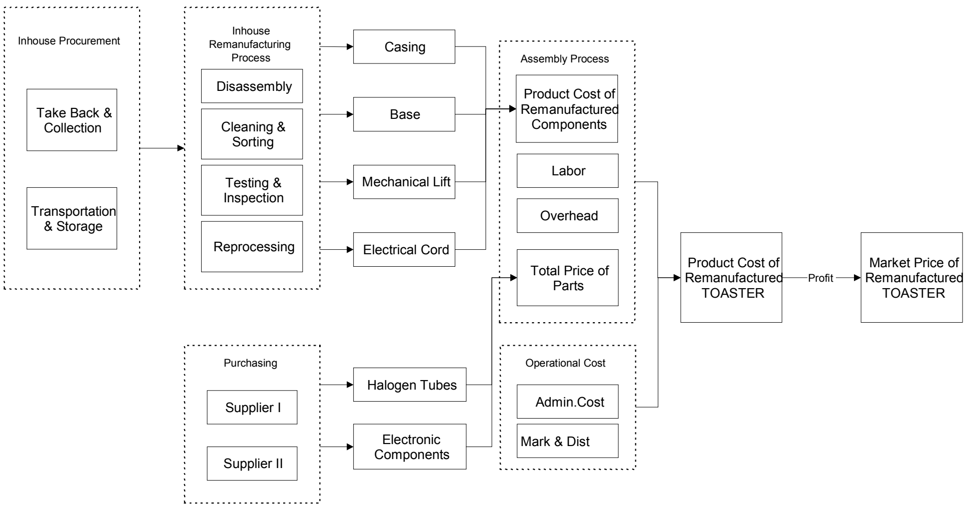


Figure 6 Production flow for remanufacturing an old toaster



3.2 Assessment model for individual parts

The proposed model has been applied for assessing the reuseability of each part and the toaster as a whole. The calculations and the results for part assessment are shown in Table 2.

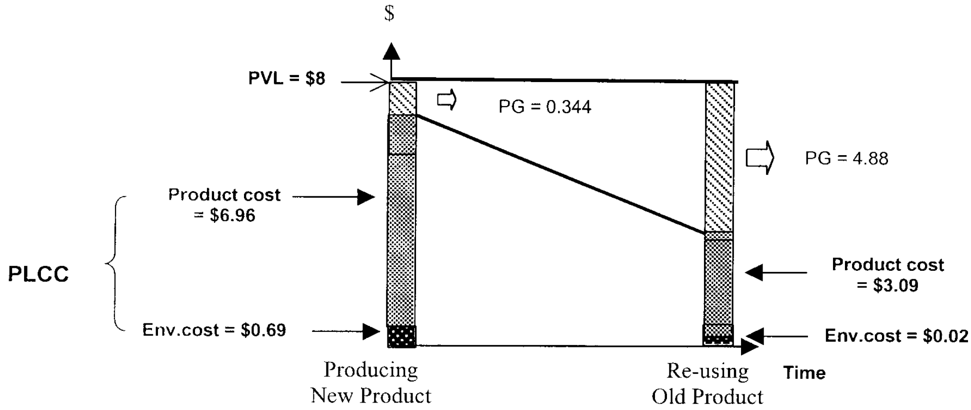
Table 2 Assessment model for individual parts

Description	*Base*	*Electrical Cord*	*Casing*	*Mechanical Lift*	*Halogen Tubes*	*Electronic components*
Producing a new part						
Product Cost	$6.96	$0.87	$2.61	$8.70	$10.43	$5.22
Environmental Cost	$0.69	$0.08	$0.26	$0.87	$1.04	$0.52
PLCC	**$7.65**	**$0.95**	**$2.87**	**$9.57**	**$11.47**	**$5.74**
Market Price (MP)	$8.00	$1.00	$3.00	$10.00	$12.00	$6.00
Product Effectiveness (PE)	1	1	1	1	1	1
PVL	**8**	**1**	**3**	**10**	**12**	**6**
PG	**0.34**	**0.04**	**0.12**	**0.43**	**0.52**	**0.25**
Remanufacturing an old part						
Procurement Cost	$1.00	$1.00	$1.00	$1.00	$1.00	$1.00
Remanufacturing Cost	$2.09	$1.57	$2.41	$1.86	$1.04	$1.02
Environmental Cost	$0.02	$0.01	$0.02	$0.01	$0.01	$0.01
PLCC	**$3.11**	**$2.58**	**$3.43**	**$2.87**	**$2.05**	**$2.03**
Market Price (MP)	$8.00	$1.00	$3.00	$10.00	$12.00	$6.00
Product Effectiveness (PE)	1	1	1	1	0	0
PVL	**8**	**1**	**3**	**10**	**0**	**0**
PG	**4.88**	**-1.58**	**-0.43**	**7.12**	**-2.05**	**-2.03**
$\Delta PG = PG_{NC} - PG_{OC}$	**-4.54**	**1.62**	**0.55**	**-6.69**	**2.57**	**2.28**

The following assumptions were made for the calculations. Some of the cost data are confidential in nature, therefore these data were calculated by using common ratios between cost components, based on the known market prices of the parts. Currently there is no proven methodology for calculating the dollar values of the environmental impacts for the product, 10% of product cost and 1% of remanufacturing cost were used to calculate the environmental cost. The environmental cost for remanufacturing is significantly lower because it does not include material production. PE indicates whether a part has reuse potential or not. The PEs of the halogen tubes and the electrical components were set to zero because they have no potential for a second life.

The cost structure for the example of the base is shown in Figure 7 in diagrammatic form.

Figure 7 Graph presentation of the base assessment



A comparison of results for all parts given in Figure 8a points out that among the potentially reuseable parts only the base and the mechanical lift have negative values of Δ PG, which are feasible for reuse. In contrast, the halogen tubes, the electronic components, the electrical cord and the casing have positive values of Δ PG, which means they are not feasible for remanufacturing. Out of four, in the first two cases the reason for the positive value is the quality status of the parts at the end of their life (PE = 0), in the second two cases the reason is the high value of PLCC (Figure 8b). The cost analysis of PLCC shows that for the electrical cord the disassembly cost (38.91%) and take back and collection cost (32.41%) are the dominating factors, whereas for the casing the reprocessing cost (31.4%) and disassembly cost (29.32%) are the dominating factors. This information can be used to generate any improvement in product design or process optimisation in order to reduce the PLCC value.

Figure 8a PG comparisons

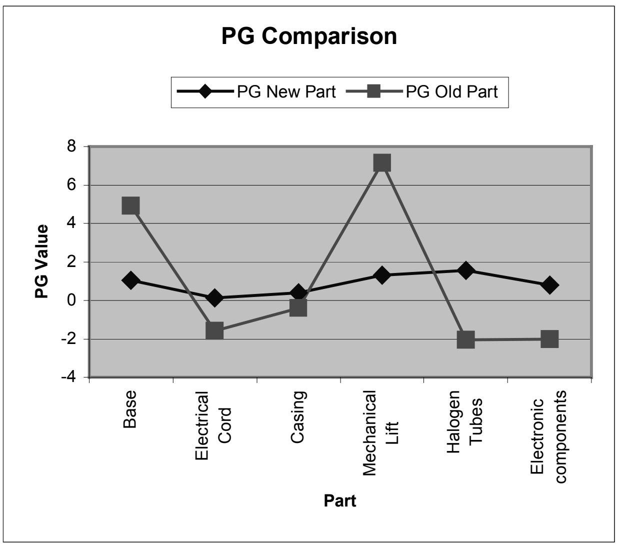
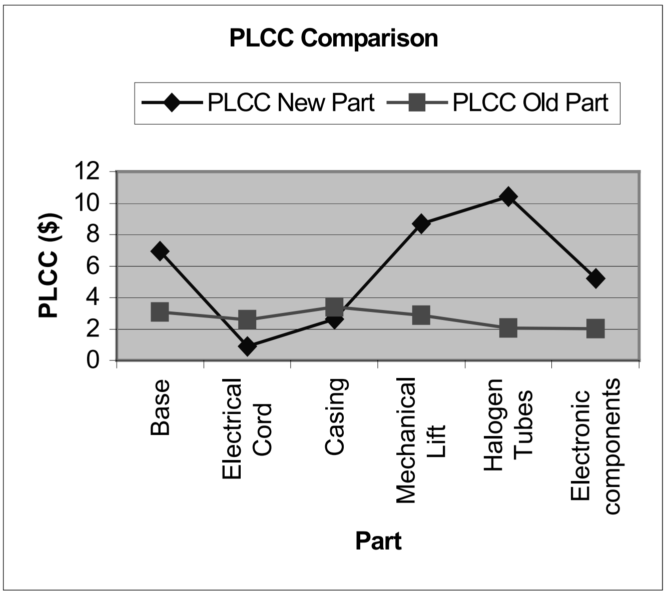


Figure 8b PLCC comparisons



In the next step, those parts that are not suitable for remanufacture are to be assessed for recycling or disposal. The results are shown in Table 3. For the casing, the halogen tubes and the electronic components the decision is fairly clear. For the electrical cord, the differences between the PLCCs are too small to justify a decision. However, since the decision is not very critical, the results can still be used as a guideline.

Table 3 PLCC calculation for recycling and disposal options

Description	*Electrical Cord*		*Casing*	*Halogen Tubes*	*Electronic Components*
	Plastic	*Copper*			
PLCC Recycling	$1.31	$0.70	$1.53	NA*	NA*
PLCC Disposal	$1.34	$0.67	$2.23	$2.04	$2.02
Preferred Option	Recycling	Disposal	Recycling	Disposal	Disposal

*NA : Not available

4 Conclusion

The model described in this paper provides a useful tool to decide on the use of a product at the end of its life. The model is based on some simplifying assumptions but it is still accurate enough for making sound decisions. Highly accurate costing figures are not essential for this purpose since the costing is used for comparison only. The new challenges in the model can be seen firstly in the estimation of the product performance, based on product lifetime monitoring, and secondly in the estimation of environmental costs, based on impact indicators. Current research is carried out to generate appropriate data in these areas.

Today, usually the environmental costs are not borne by the manufacturers but by the community at large. Including this cost factor in the model means that the outcomes can easily become negative. However, by setting the environmental costs to zero, the model can still be used in a cost driven environment, indicating the advantages of a reuse strategy.

References

1 Haberland, S., Mager, A. and Waltemath, A. (1997) 'Logistic strategies for the realization of a life cycle economy', *Life Cycle Networks: Proceedings of the 4th CIRP International Seminar on Life Cycle Engineering*, Berlin, Germany, 26-27 June, pp.43-55.

2 Hata, T., Kimura, F. and Suzuki, H. (1997) 'Product life cycle design based on deterioration simulation', *Life Cycle Networks: Proceedings of the 4th CIRP International Seminar on Life Cycle Engineering*, Berlin, Germany, 26-27 June, pp.59-69.

3 Hata, T., Sakamoto, H., Kato, S., Kimura, F. and Suzuki, H. (1998) 'Feasibility study for rapid product life cycle', *Proceedings of the 5th CIRP International Seminar on Life Cycle Engineering*, Stockholm, Sweden, 16-18 Sept., pp.151-160.

4 Hata, T., Sakamoto, H., Kato, S., Kimura, F. and Suzuki, H. (2000) 'Product life cycle simulation with quality model', *Proceedings of the 7th CIRP International Seminar on Life Cycle Engineering*, Tokyo, Japan, 27-29 Nov., pp.60-67.

5 Steinhilper, R. (1998) *Remanufacturing: The Ultimate Form of Recycling*, Fraunhofer IRB Verlag, Stuttgart.

6 Zussman, E. (2000) 'Linking remanufacturing process and product design', *Proceedings of the CIRP International Seminar on Life Cycle Engineering*, Tokyo, Japan, 27-29 Nov., pp.249-255.

7 Kaebernick, H., Anityasari, M. and Kara, S. (2001) 'Reuse or recycling industrial products: a technical and economic model for decision support', *Proceedings of the 8th CIRP International Seminar on Life Cycle Engineering*, Varna, Bulgaria, 18-20 June, pp.37-47.

8 Fleischer, G., Rebitzer, G., Schiller, U. and Schmidt, W.P. (1997) 'EuroMat'97 – tool for environmental life cycle design and life cycle costing', *Life Cycle Networks: Proceedings of the 4th CIRP International Seminar on Life Cycle Engineering*, Berlin, Germany, 26-27 June, pp.107-120.

9 Westkamper, E. (2000) 'Life cycle management: approaches and visions towards sustainable manufacturing', *Proceedings of 7th CIRP International Seminar on Life Cycle Engineering,* Tokyo, Japan, 27-29 Nov., pp.1-16.

10 Dhillon, B.S. (1989) *Life Cycle Costing,* Gordon and Breach Science Publishers, New York.

11 Pecht, M. (Ed) (1995) *Product Reliability, Maintainability, and Supportability Handbook,* CRC Press, New York, USA.