Design for Disassembly and the Environment

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Abstract

The financial and environmental consequences of disassembly and recycling at the end of a product's life are studied. Analyses of a small coffee maker and some large domestic appliances are presented. It is shown that redesign proposals resulting from Design for Assembly analysis are compatible with Design for Disassembly and that significant improvements are achievable. It is also shown that optimization of the disassembly sequence is important in order to maximize any financial benefits, but that to minimize environmental impact considerations additional to Design for Disassembly should be taken into account. Criteria to determine the point at which disassembly should cease are discussed

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Introduction

There is a growing interest in product design for disassembly [1,2] and in life-cycle analysis(LCA) for environmental impact evaluation [3,4,5]. Factors which should be considered in the design of products for ease of disassembly are (i) the financial aspects, including costs of the disassembly process, the cost of benefits of item reuse or recycling costs of disposal and (ii) environmental impact. In this research, procedures for product evaluation taking into account these factors have been investigated together with the manipulation of the disassembly sequence for cost optimization. For environmental considerations, a method suggested by TNO was used which takes into account the effects of Materials, Energy and Toxicity (MET) on the environment [6].

Financial Analysis for a Domestic Coffee Maker

To illustrate the use of these product analysis procedures, the example of a small coffee maker is considered, Fig. 1. As a first step in the disassembly analysis, a Design for Assembly analysis was carried out using DFA software: The product consisted of 74 parts with 10 subassemblies and had a total of 84 items assembled. The DFA assembly time was estimated to be 660s. Some 69s of assembly time was due to fasteners and only 9 items were considered to be theoretically required. The coffee maker used 12 different materials and weighed 1.81 kg.

From the results of the DFA analysis a disassembly sequence was generated on an Excel spreadsheet, with the following additional disassembly information:

1. The end of life destination for each item: reuse, recycle or landfill disposal with regular or special treatment.
2. The value or cost attributable to each item as a result of its end of life destination.
3. The labor cost for the disassembly of each item.
4. The cost of disposal of the remainder of the product (the rest fraction) at each step in the disassembly sequence.
5. The "total profit" at each step in the disassembly sequence. This is the sum of the reuse/recycle values or the negative disposal values, the cumulative cost of disassembly, and the cost incurred for disposal of the remainder of the product (the rest fraction).
6. The "effect" of each step in the disassembly sequence. This is the difference between the current total profit and the total profit at the previous step.

Any point on the financial line depicts the cumulative cost of disassembly, the cumulative profits or losses resulting from items that are to be recycled, reused, or disposed, and the cost of disposal of the remainder of the product without further disassembly. The initial disassembly sequence of the coffee maker was arbitrary being a reversal of the DFA assembly lists. Some editing of the disassembly steps was necessary. For example, parts made of the same or of compatible materials *not separated for the purposes of reuse, recycling, or* special disposal, were combined and treated as one item. Appropriate disassembly procedures were assumed where soldered wires were simply cut. The financial line for this edited sequence is shown as the lower curve in Figure 2. Disassembly would certainly cease after 447s when the last part of any value, the heater plate, had been removed. The *remainder of the product* would be disposed of without disassembly. At this point, a cost of $0.81 would have been incurred.

Financial Optimization of the Disassembly Sequence

For this discussion, an item requiring special waste treatment such as a printed circuit board (PCB) will be referred to as a toxic item. It can be seen in Fig. 2 that, when the PCB was removed from the coffee maker, there was a positive effect on the financial line even though the PCB was assumed to have no value. This was because when the last toxic item is removed from an assembly, the rest fraction disposal rate will change from special treatment (high rate) to non-toxic treatment (low rate). The earlier the last toxic item is removed, the greater the positive influence on the financial line. Thus, in order to maximize the effect of removing the last toxic item, a good rule is to remove all the toxic items as early as possible.

The disassembly financial line begins at a negative value representing the disposal cost of the entire product and will rise whenever significant profits are gained from component reuse or recycling. The line will fall when labor cost and disposal fees exceed any profits. In order to increase profits or decrease loss during disassembly, the most valuable parts should be removed as soon as possible and disassembly can be stopped when the marginal return on investment becomes unfavorable. A systematic procedure has been developed to rearrange the disassembly sequence to give the maximum return as early as possible, within the constraints of disassembly precedences. To determine the order in which valuable items should be removed, the yield for each of these is calculated. This yield can be defined as the sum of all the cost effects divided by the sum of the disassembly times for all of the items that must be removed before the valuable item.

In the optimization procedure the "valuable" items were removed starting with the item having the highest yield. In the case of the coffee maker, this was the sheet metal base. Once the last critical item was removed, in this case the heater plate, no further rearrangement of the disassembly sequence was necessary. The optimized disassembly sequence for the coffee maker is shown in Fig. 2, compared to the initial disassembly sequence. Disassembly should again cease when the heater plate is removed, after 333s with a loss of $0.52.

Coffee Maker Redesign

To study the effects of a possible redesign of the coffee maker, some of the suggestions resulting from the DFA analysis were implemented. A reduction in total assembly time from 660s to 473s was estimated. The assembly time due to separate fasteners was reduced from 69s to 14s and the number of different materials reduced from 12 to 8. The total number of items in the assembly would be reduced from 84 to 58.

The financial lines for the original and redesign of the coffee maker are shown in Fig. 3 (upper two curves). The DFA redesign reduced the disassembly time from 333s to 130s while the financial loss was reduced from $0.52 to $0.09. Correspondingly, the rate of loss was reduced from $5.62/hr to $2.49/hr. For the original design, the best financial scenario would be to dispose of the entire product without any dismantling, incurring a loss of $0.20. However, with the new design, the least cost situation would be to dismantle the coffee maker for 130s at a loss of only $0.09.

Environmental Assessment for the Coffee Maker

Assessment of the environmental impact during initial manufacture and end-of-life disposal has been achieved using a single figure environmental indicator developed initially at the TNO Product Centre [6]. This method has been chosen because the results are more readily understood and interpreted by designers than the complex data developed from the full life-cycle-analysis (LCA) procedures. MET-points can be subdivided into the M, E and T origins (Material cycles, Energy use and Toxic emissions), thus indicating the nature of the environmental impact. MET-points are calculated by making a life cycle analysis (LCA) of a material or a product and the effects quantified are:

Material Cycles: Exhaustion of Resources
Energy Use: Greenhouse effect, Acidification, Smog, Eutrophication
Toxic Emissions: Ozone Depletion, Human Toxicity Ecotoxicity

In order to carry out the environmental impact analysis of the products, data on MET points per unit have been used based on effect targets from the Netherlands.

Each item in the products investigated has been assigned an end-of -life destination. For recycling a quality figure has been applied to account for contamination or degradation of the materials in determining the MET points "released" through recycling. Items such as printed circuit boards and CRT glass have been assumed toxic and require special disposal methods until removed from the assembly, after which they are processed for recycling of materials. The main assumptions in all analyses are:

(i) The disassembly processes for the product have negligible environmental impact (MET points) since manual disassembly methods are assumed.
(ii) Recycling of an item results in effective recovery or release of the MET points for initial material manufacture.
(iii) Reuse or remanufacture of an item results in effective recovery of the MET points for both initial material manufacture and manufacturing processes.
(iv) The rest fraction of the product at any stage of disassembly is assumed to be disposed of by

special waste methods as long as an item requiring special waste treatment remains, after which regular waste disposal methods are assumed. For all materials, special waste disposal results in lower MET points per unit weight than regular waste disposal methods.

Figure 3 shows financial and environmental assessment curves for the disassembly of the coffee maker, and the vertical axis represents MET points, as disassembly proceeds. A stage is reached when further disassembly will cause no further improvement in environmental impact, because the remaining items are all disposed of in the same manner in the rest fraction. This point also corresponds to the point in the financial disassembly analysis at which further removal of parts results in no increased financial benefit.

For the environmental lines for the coffee maker, the least environmental impact occurs where the last recycled or reused item is removed. For the original design this occurs after 333s of disassembly time and for the redesign at 130 s of disassembly time. The net environmental impact of the two coffee makers is about the same , because the material content and manufacturing processes used are similar. It is not surprising that with small products such as the coffee maker, the cost of dismantling and disposal will outweigh the financial benefits of recycling. However, redesign and optimization of the disassembly sequence in these cases can reduce the financial losses considerably.

Disassembly of Large Products

To study the disassembly of larger products, a washing machine, a refrigerator and a TV set were analyzed. Figures 4, 5, 6 compare the financial and environmental lines for the original designs and for DFA redesigns. Unlike the coffee maker, a profit can be made through disassembly and recycling of larger appliances. Disassembly time has been considerably reduced by the DFA redesigns. On average, disassembly time has been reduced by 48% and the profits increased by 6%. However, the average rate of profit has increased by 109%. Unlike the coffee maker, it appears that, in both the present and redesign of the larger appliances, the best financial scenario would be just short of full disassembly.

The environmental impact assessment lines for the three appliances follow similar trends. The refrigerator (Fig. 5) has significantly greater environmental impact than the other two appliances. This results from the use of CFC based coolants and foaming agents for the insulation. The positive step in the curves results from collection and reprocessing of the refrigerant. In all cases the DFA redesign has a similar overall environmental impact compared with the corresponding original design. This is because the material content is essentially the same, but in all cases the redesign results in reduced disassembly times.

When to Stop Disassembly

There are many criteria that might be used in deciding when to stop disassembly. For example, the point of maximum profit or minimum loss might be selected. For the larger appliances, the disassembly sequence has little effect on this point and it might be concluded that complete disassembly is advisable. However, profits close to the maximum can be achieved in a much shorter time with the optimized sequence. An alternative is to stop disassembly when the highest rate of profit is achieved. This can be determined by dividing the profit at any point on the financial line by the disassembly time.

The highest rate of profit obtainable for the larger appliances is after the removal of only a few critical items. In these cases, the effect of the redesign is not very significant. However, it is unlikely that the removal of only a few items from the assembly and disposal of the remainder would be satisfactory from an environmental point of view. As can be seen for the washing machine and TV set (Figs. 6 and 7) stopping disassembly at the point of maximum profit rate would result in only a small proportion of the environmental impact improvement from disassembly and recycling being realized. Clearly a compromise between least environmental impact and greatest financial return is necessary.

Conclusions

The financial lines for disassembly of several products have been compared. In all cases, the benefits of redesign suggested by a DFA analysis have been clearly shown. It appears that typical DFA redesigns will be equally beneficial in simplifying disassembly at the end of product life. However, in addition to the usual DFA suggestions, design changes should also be considered that will simplify the easy removal of critical items. Also, recyclable materials should be employed rather than materials that necessitate disposal both to improve the financial picture and to reduce environmental effects.

The small coffee maker and the much larger appliances provided two distinctly different situations. It can be concluded that it will be very difficult to overcome the labor costs involved in disassembling smaller products. When cost is the only consideration, a recycling center may not always continue disassembly until all critical items are removed from products because often the maximum rate of profit is achieved earlier. However, the final decision may need to take into consideration additional factors such as the number of products to be recycled, the capabilities of the recycling facility, and the overall environmental effects.

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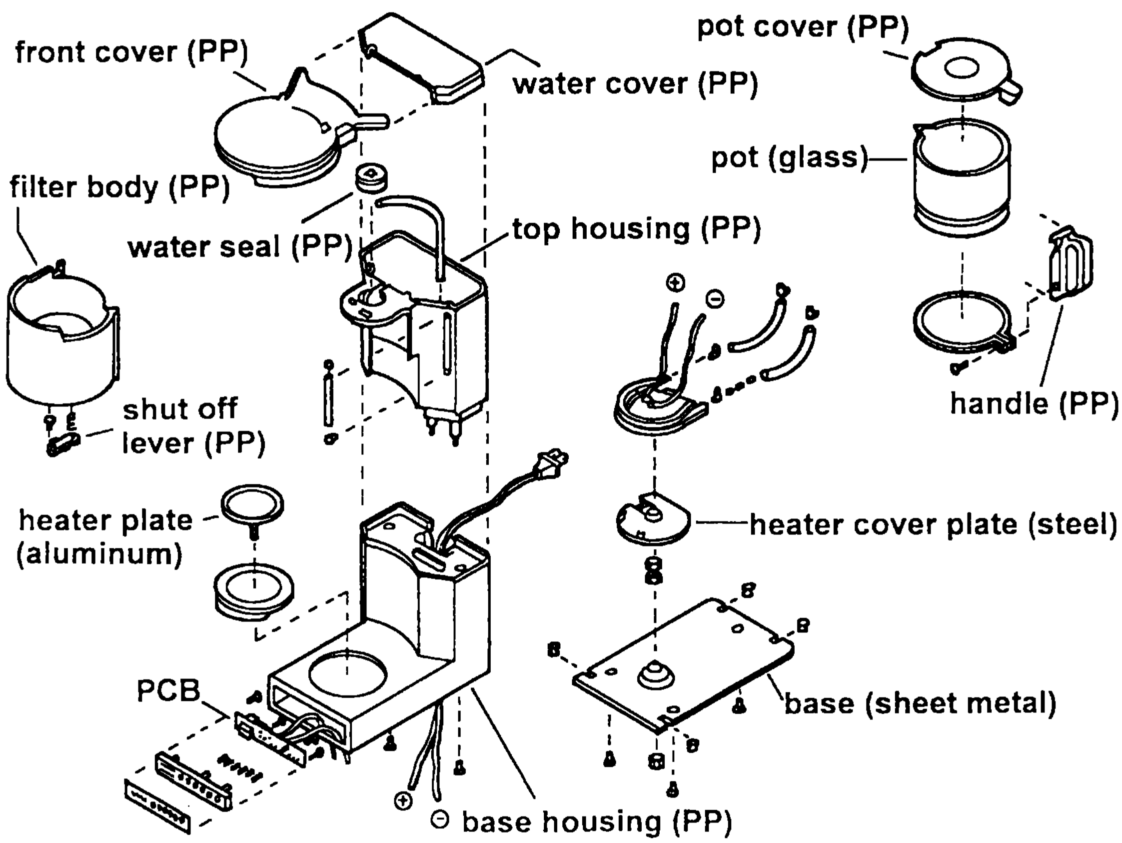

Figure 1 Exploded view of coffee maker

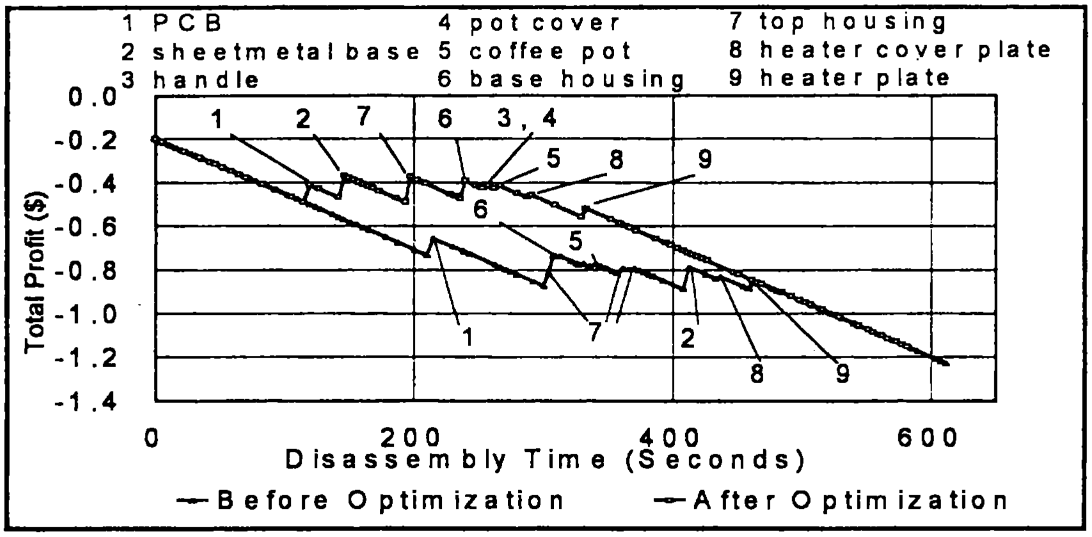

Figure 2 Financial disassembly analysis of the coffee maker

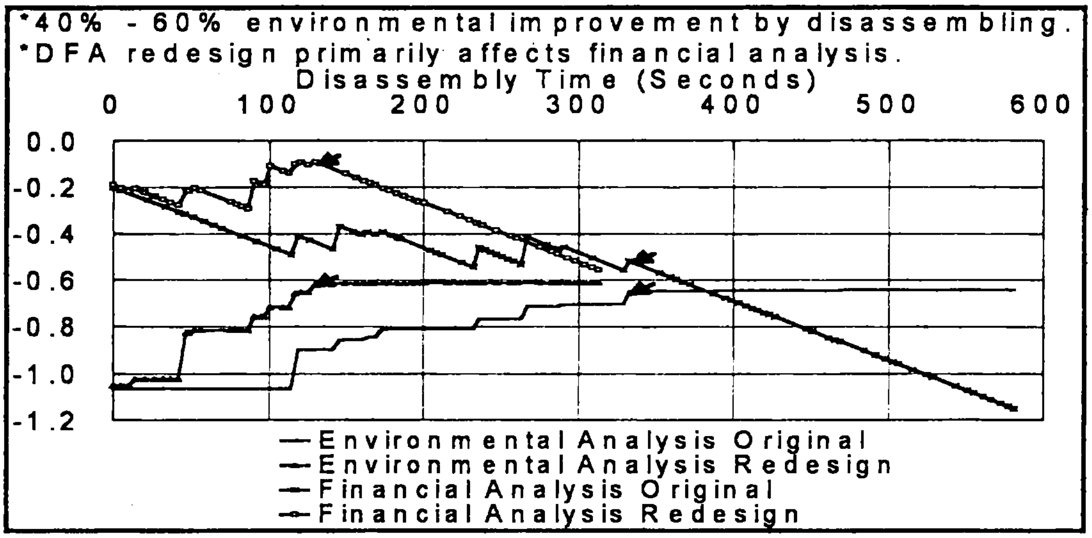

Figure 3 Disassembly analyses of original and redesigned coffee maker

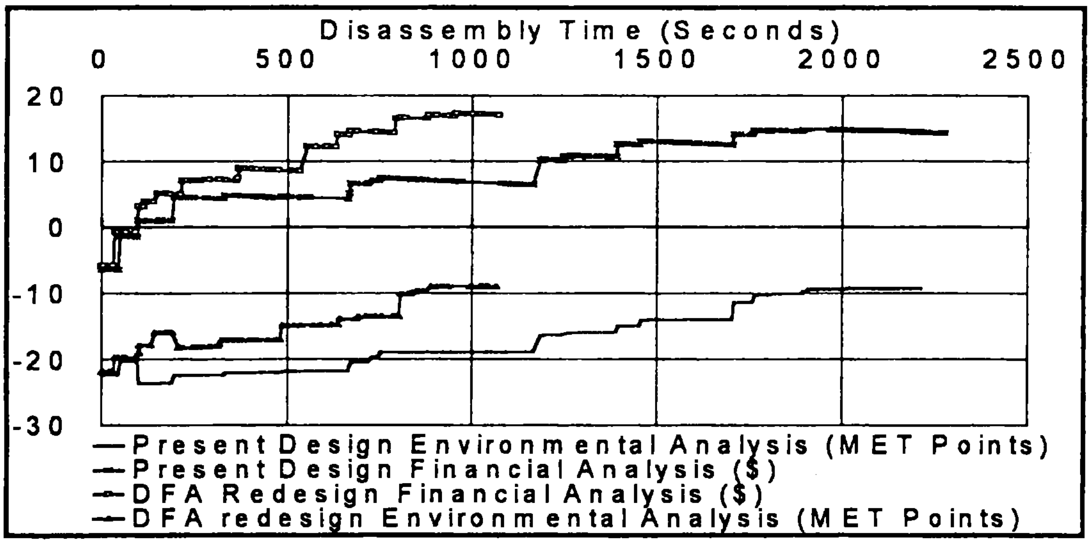

Figure 4 Disassembly analyses of an automatic washing machine

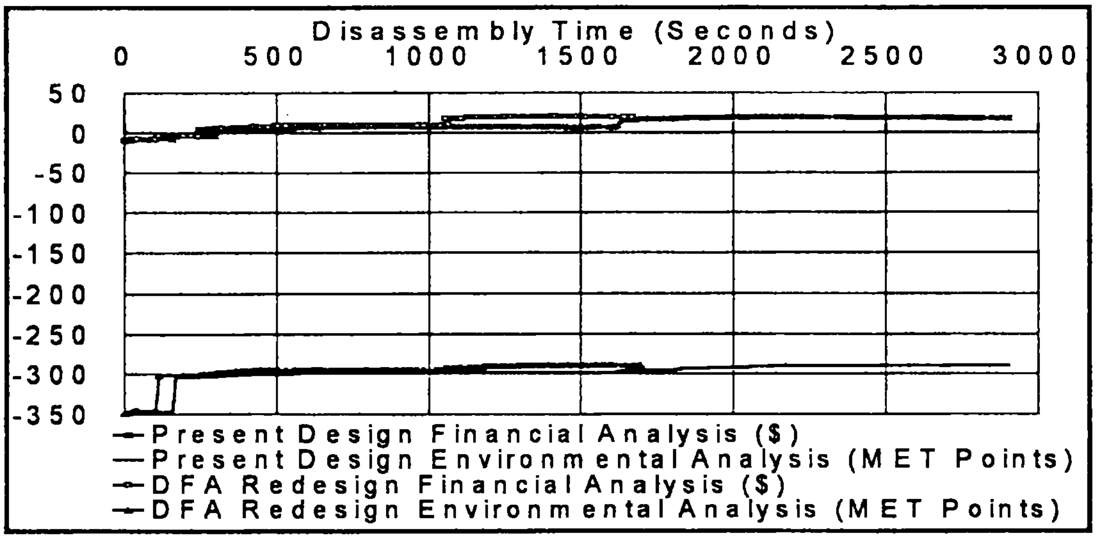

Figure 5 Disassembly analyses of a refrigerator

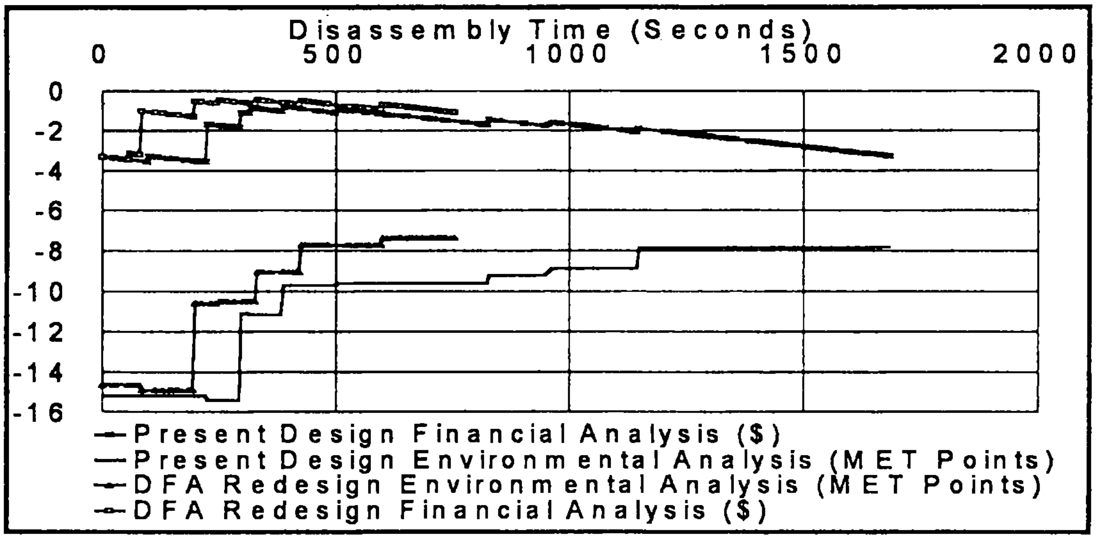

Figure 6 Disassembly analyses of a color TV set