Product Design for Disassembly and Bulk Recycling

M. Sodhi, W. A. Knight (2)
University of Rhode Island, USA
Received on January 7, 1998

The recycling of manufactured products depends greatly on the efficiency with which material can be separated from each other. For the long term, recycling can be made more effective by the design of products for greater use of disassembly and recycling. This requires the development of suitable product analysis tools to enable design teams to evaluate the ease of disassembly and recycling of alternative product concepts during the early stages of design. This paper describes the development of product analysis procedures for combined disassembly and bulk recycling such that consequences of material selection upon the end-of-life recovery of materials can be investigated.

Keywords: Design, Disassembly, Environmental

1.0 Introduction.

Public awareness and increased legislation are placing pressure on the development of effective take back and recycling of manufactured products at end-of-life. However, the various materials in manufactured products only have significant recycled value when they are divided into clean separate types. The viable recycling of manufactured products depends greatly on the efficiency with which materials can be separated from each other. The separation and recovery of items and materials from products for recycling can be approached by relatively careful disassembly, with subsequent manual sorting of materials and by bulk recycling, which involves the shredding, followed by various mechanical separation processes on the resulting material mix. In the long term, recycling can be made more effective by the design of products for greater ease of disassembly and recycling. This requires the development of suitable product analysis tools to enable design teams to evaluate the ease of disassembly and recycling of alternative product concepts during the early stages of design. This paper describes the modeling of bulk material separation and incorporation of these results into previously developed product analysis procedures [8], which enable design teams to evaluate the recycling potential of proposed products.

2.0 Disassembly Analysis of Products.

The discussion of and analysis of the disassembly of products has lately been receiving attention [1,3-5,8], including recently, product analysis tools that enable a balance between the financial and environmental aspects to be evaluated [8]. These procedures build on previous and widely applied methods for design for manufacture and assembly [2]. Application to the analysis of large consumer products has been described elsewhere [8].

The purpose of the procedures for product analysis is to simulate disassembly at end-of-life and to quantify the resulting cost benefits and changes in environmental impact. Disassembly costs are determined from time-standard databases for end-of-life disassembly processes. Each item in the assembly is allocated to an appropriate end-of-life destination (recycle, reuse, regular or special disposal and so on) based on its material content and this information, together with the item weight, enables the possible costs or profits to be determined from an appropriate materials database. The user also provides information of the disassembly precedence of each item by indicating those items that must be removed immediately prior to the component under consideration in order for it to be released from the assembly. This information enables the best disassembly sequence, which removes valuable items as early as possible, to be determined and details of this procedure have been described previously [8].

A typical financial assessment graph is shown as the upper line in Figure 1, for the disassembly of a telephone answering machine. This shows the return or cost as disassembly of the product progresses and is plotted against disassembly time. A point on this curve represents the profit or net cost if disassembly is stopped at this stage. The first point represents the costs of product disposal by landfill or incineration (user selected) without disassembly, which includes the take-back costs of the product (collection, inventory, etc.). Included in the contributions to each point on the graph are the following:

- the take-back cost of the whole product
- the cost of disassembly up to this point
- the cumulative value(from recycling or reuse) of items disassembled to this point
- the cost of disposal of the remainder of the product yet to be disassembled (rest fraction).

Generally at the start of disassembly small items (fasteners, etc.) are removed for which the cost of disassembly is greater than the value of any material recovered and the graph goes down. Some items will have a significant positive effect on this financial return analysis. This will be the case for items that have high recycle values, are reused or are toxic (the rest fraction of the product becomes less costly to dispose of once these items are removed). These items are referred to as critical items. The curve shown in Figure 1 is typical of small products for which the material content is not sufficient for recycling values to compensate for the labor cost of disassembly, with the main printed circuit board (PCB) being the only item of significant value, in this case. However, bulk recycling of all or part of the product may be more appropriate.

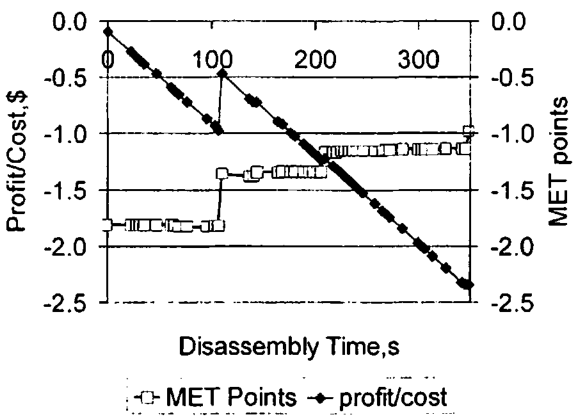

Figure 1 Answering Machine Disassembly Analysis

Assessment of the environmental impact during initial manufacture and end-of-life disposal has been achieved using the single figure environmental indicator, MET points [6]. This method has been chosen because the results are more readily understood and interpreted by designers than the complex data often developed from the full life-cycle-analysis (LCA) procedures which are also available. MET-points are based on calculations from a life cycle analysis of a material or a product.

The environmental impact assessment results are summarized in curves which show the net MET points at any stage of disassembly. The lower line in Figure 1 shows a typical example for the answering machine. A specific point on the curve represents the net environmental impact of the product if disassembly is stopped at this stage. Details of this form of environmental assessment have been given previously [8].

3.0 Analysis of Bulk Recycling

Bulk recycling typically involves several processing steps, beginning with size reduction (shredding), followed by a series of separation processes, which use differences in material properties (e.g. density, magnetic properties, melting point, etc.) to discriminate between materials. In general the yield from these processes is not 100 percent so some target material will be left in the rest fraction or another target fraction, which may reduce its potential value. Size reduction involves conversion of an input batch of products into flakes of a uniform size. In practice a wide range of shredder-grinder combinations are used to do this task. Once an input stream of homogeneous size is generated, magnetic separators remove ferrous metals. Fines and air classification extracts the light and fluffy materials, which could be problematic when mixed with liquids. Eddy-current separation is most commonly used for non-ferrous metals. Economic models for determining the operating costs of these processes have been developed [9].

The commonly used methods for separating plastics utilize density. One particular implementation of density separation is the "sink-float" method in which a stream of shredded material is passed through successive liquid baths of different densities. The material with a density greater than that of the bath liquid sinks to the bottom and the rest floats to the top. The sediment and float material streams are again processed in baths of different densities, and this process is continued until all the target materials are isolated. Another similar separation process is the hydro-cyclone process in which materials are separated by large centrifuges. While the mechanics of separation are different, the operational characteristics are essentially the same as the sink-float method, and thus models developed for the sink-float technology are applicable to hydro-cyclone methods as well.

Density separation techniques for plastics involve several passes of the material submixes. Thus, while the process of separation itself is quite simple, an operational issue is that of determining the order in which the materials should be separated. Consider the following material mixture (indexed, according to increasing density) to be separated:

Material	1	2	3	4	5	6
Volume m^3	12	6	7	17	18	11

If the materials are separated in sequence (i.e. material 1, followed by 2, 3 and so on), the total volume of material processed is 259 m^3. However, consider the sequence shown below. It is evident that the separation sequence used can reduce the amount of material handled (44% in this case). The time required to process a batch depends on the total volume processed and the best separation sequence minimizes the total amount of volume processed. The best processing sequence is dependent on the relative volumes of materials in the specific mix.

Pass	Materials Separated	Volume Processed (m^3)	Split between
1	1 - 4, 5 -6	71	4,5
2	1 -3, 4	42	3,4
3	1, 2 - 3	25	1,2
4	2,3	13	2,3
5	5,6	29	5,6
	Total Volume Processed		180 m^3

There are (n-1)! ways of separating a n material mixture. The problem can be modeled in various ways, but a dynamic programming recursion leads to an efficient solution procedure [10] for a given multi-material mix. Let g(i,j) be the least volume processed to separate a mixture of (j+1) materials, composed only of materials i through (i+j). Now g(i,0) = 0 since no processing is required to separate a single material. Again, g(i,1) = $v_i + v_{i+1}$. To compute g(i,2), observe that two passes are necessary to separate this three material mix. The volume processed in the first pass is always ($v_i + v_{i+1} + v_{i+2}$). Now the volume processed in the second pass is either ($v_i + v_{i+1}$) or ($v_{i+1} + v_{i+2}$), depending upon whether the first separation is between materials 2 and 3 or 1 and 2. Thus:

$$g(i,2) = \sum_{k=1}^{k=i+2} v_k + \min(v_i + v_{i+1}, v_{i+1} + v_{i+2})$$

Following this reasoning, the recursion for the general case is:

$$g(i,j) = \sum_{k=1}^{k=i+2} v_k + \min_{m=1\ldots j}\{g(i, m-1), g(i+m, j-m)\}$$

This recursion provides an efficient method of computing the optimal separation sequence and the associated volume. The optimal sequence shown above was determined in this way.

4.0 Disassembly and Bulk Recycling

The methods for analyzing product disassembly described in section 2 do not include bulk recycling as an end-of-life destination for all or part of the product. In practice when products are processed at end-of-life, a combination of disassembly, bulk recycling and disposal by landfill or incineration will be used. For efficient processing it is necessary to determine the best combination of these processes for a given product. In practice some disassembly will be necessary to remove any hazardous items such as batteries, capacitors, etc., before bulk recycling takes place. Thus if bulk recycling is appropriate, then design modifications to release these items as soon as possible during disassembly will be important.

Consider the example of the telephone answering machine. The financial analysis in Figure 1 does not include bulk recycling as an end-of-life destination and the rest fraction is assumed landfilled. Figure 2 shows the cost of this rest fraction disposal as disassembly proceeds, which obviously reduces as the rest fraction gets smaller. The large cost reduction at step 13 corresponds to removal of the main printed circuit board (PCB). This is the last item to be removed, which requires special waste treatment, and subsequently the rest fraction can be disposed of less expensively.

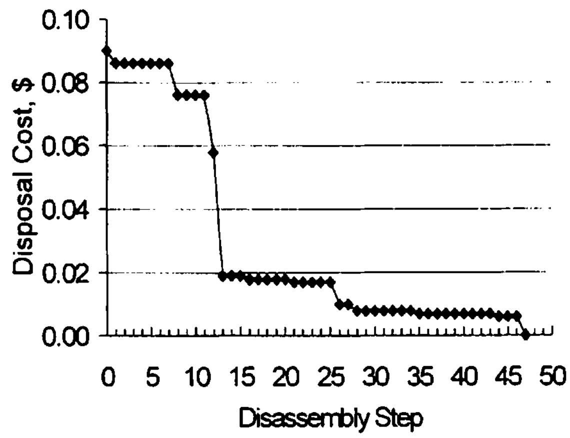

Figure 2 Rest Fraction Disposal Cost

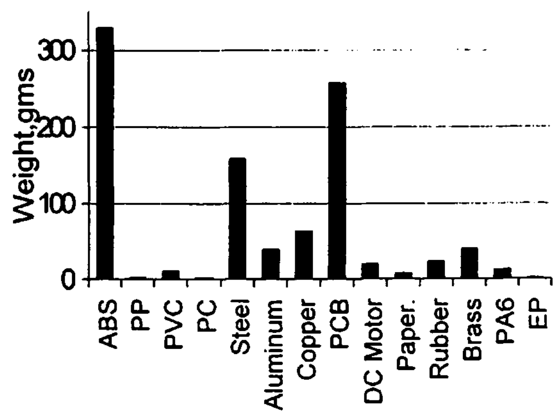

Figure 3 Material Content of Answering Machine.

Figure 3 shows the breakdown of the main materials in the answering machine by weight. The steel and non-ferrous metals will be effectively separated by magnetic and eddy current separation, which may also remove some proportion of the shredded printed circuit board and DC motor. Density separation can be used to separate the remaining plastics and the residue of the PCB and DC motor. The density separation process can in practice discriminate between materials with specific gravity differences of 0.04 or more. This means that, in this case, the PA6, EP, PC and PVC cannot be separated from the higher density residue of the PCB. Thus the possible target materials become the PP, rubber, ABS and the higher density residue. Since this residue will be mainly shredded PCB material this can be smelted to recover precious metals such as gold, palladium, etc., but at reduced value due to dilution by the other materials after separation. Assuming typical market values for the materials and typical processing costs and efficiencies, the procedure outlined in Section 3.0 is used to determine the economic processing sequences for these materials, mainly to isolate the reasonably large quantity of ABS present in the product.

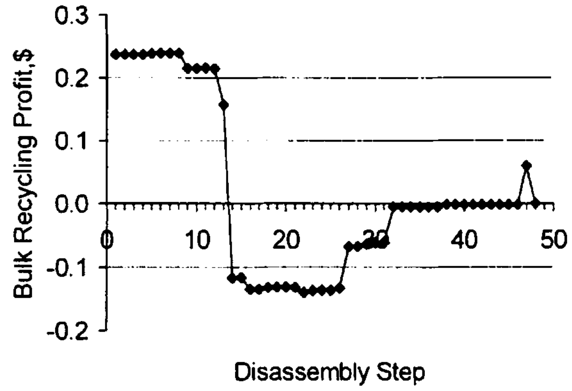

Figure 4 Profit/Cost of Bulk Recycling Rest Fraction

Figure 4 shows the profit or cost from bulk recycling of the rest fraction of the product as disassembly proceeds. The large drop at step 13 again results from removal of the PCB, which is the main item of significant value in the product. After this stage bulk recycling results in a net loss, but in comparison with Figure 2 this is seen to be generally less costly than landfill disposal of the rest fraction.

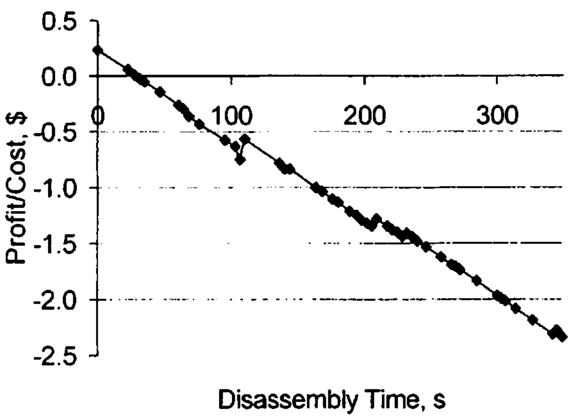

Figure 5 Disassembly Analysis with Bulk Recycling

Figure 5 shows the net profit or cost as disassembly proceeds, with bulk recycling of the rest fraction used in place of landfill disposal as appropriate. Figure 6 compares this financial line with that from Figure 1. This result confirms that small products, such as this answering machine, should be bulk recycled without disassembly, as this is the most economic. Designers should therefore concentrate on selecting materials and assembly methods that result in the most efficient separation of incompatible materials by bulk recycling methods. Useful discussions on design guidelines for bulk recycling can be found elsewhere [1,7]. For larger products which can potentially result in a profit from disassembly, the inclusion of bulk recycling of the rest fraction may alter the optimum economic level of disassembly.

4.0 Concluding Remarks

In practice combinations of disassembly, bulk recycling and disposal by landfill or incineration will be used at product end of life and determining the most appropriate combination for a product is necessary. The procedures outlined in this paper enable design teams to effectively simulate the end of life disposal of products and to determine the effects of material choices and assembly methods, which will facilitate the design of products for better recycling. This in the long term is the best means of improving recycling efficiency, leading to industries becoming more self-sustaining in terms of materials, with corresponding environmentally beneficial effects.

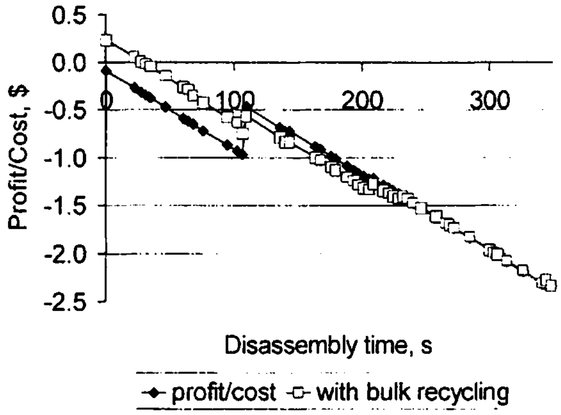

Figure 6 Results Comparison

References

[1] Alting, L. and Boothroyd G., 1992, Design for Assembly and Disassembly, Annals of CIRP, 41/2:625 - 636.

[2] Boothroyd, G., Dewhurst , P., Knight, W. A., 1994, Product Design for Manufacture and Assembly, Marcel Decker, NY.

[3] Glen, P., Kroll, E., 1996, Diane: Disassembly Analysis Software for Product Recycling, National Design Show, Chicago, March: 1-15.

[4] Johnson, M.R., Wang, M.H., 1995, Planning Product Disassembly for Material Recovery, Int. J. of Production Research, 43:3119 -3142.

[5] Jovane, F. et al, 1994, A Key Issue in Product Life Cycle: Disassembly, Annals of CIRP, 42/2: 651-658.

[6] Kalisvaart, S.,van den Broek, J., 1996, Design for Bulk Recycling, Proc. Int. Forum Product Design for Manufacture and Assembly, Newport, RI, June:1-12.

[7] Kalisvaart, S., Remmerswal, J.,1994, The MET Points Method- a new single figure environmental performance indicator, Proc. Integrating Impact Assessment into LCA, SETAC, Brussels: 55-61.

[8] Rapoza, B., Harjula, T., Knight, W.A., Boothroyd, G., 1996, Design for Disassembly and Environment, Annals of CIRP, 45/2: 109 - 114.

[9] Sodhi, M.S., Young, J., Knight, W.A., 1997, Modeling Material Separation Processes in Bulk Recycling, to appear in Int. J. of Production Research.