Material Selection Issues in Design for Recyclability

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ABSTRACT

This paper describes a methodology to evaluate the modularity and material selection of product designs from the recyclability viewpoint. Product modularity is particularly important for electromechanical products such as computers, telecommunication devices, and peripherals. The short technology life-cycle of many of the functions in these products, combined with the customer demand for wide variety of features, necessitates product designers to optimize the modularity of components for manufacturability and serviceability. Our design for recyclability method focuses on the dismantling process that must accommodate the wide variety (product family) as well as changes over time (product generations). A case study of an inkjet printer revealed that number of different materials used in a product family is the most influential factor that determines the material recovery and scrap rate. The paper proposes the use of a design chart, the *recyclability map*, to aid in material selection for enhanced recyclability. Further, we outline the need for a material recyclability database that is required to construct the design chart.

INTRODUCTION

The recent push for design for environment (DFE; Allenby, 1993) urges designers to include environmental impact among many other product requirements. There are several perspectives in analyzing a product's impact on the environment. Life Cycle Assessment (LCA) is a broad methodology for identifying environmental burdens that arise from a product (SETAC, 1991; US EPA, 1993) from manufacture to use and eventual disposal. So far, most LCA studies have focused on single material products such as disposable drink containers and diapers. For complex products, LCA is often too time consuming for designers to implement themselves. Allenby’s DFE methodology (1993) provides a more qualitative evaluation of designs and is more applicable to early stages of design. Product take-back laws in Europe (Beitz, 1993) and the recyclability laws in Japan (Hattori and Inoue, 1992) demand a more focused goal of design for recyclability. The key is the "simultaneous" planning for post-life use of the product in the early stages of design, i.e., design for product retirement (Ishii et al. 1992; Marks, et al. 1993). Selection of materials from their life-cycle perspective is one of the most important factors influencing product recyclability (Ishii et al, 1994.)

This paper takes the viewpoint of the demanufacturing plants or recycling organizations (Figure 1). Here, one must consider not only one model of a product but the recyclability of the entire product line, i.e., product families. Further, the recycling organization must handle multiple generations of products since they are fed from any stage of the supply chain involving different model years (Ishii et al., 95.) In some cases, recycling organization may have to process products from different manufacturers. Designers must select materials on the basis of not just one model of a product, but consider the materials used in the entire product family over multiple generations.

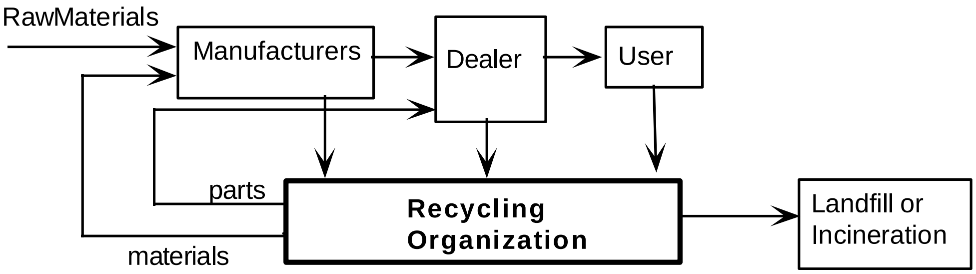


Figure 1. Design Method focusing on Recycling (Demanufacturing) Process

To enhance component reuse and material recycle, engineers must embed strategic modularity into the product and reduce the cost to the recycling organizations. Such effort will lead to overall improvement of industrial ecology through reduction of raw material use, energy use throughout the product life-cycle, and solid waste.

We view material selection to be a key issue in effective design for recycle modularity. Most designers recognize that they should use as few types of material as possible to enhance recyclability. Further, designers must consider ease of separation for components with different material sets that do not have established separation technology after grinding. Designers must also apply these principles across the entire family so that one recycling plant can effectively process the different models and generations. Whereas these general design principles have been widely recognized, most designers place low priority to recyclability criteria in view of other functional and cost requirements.

The key issue is the up front consideration of recycle modularity at the early stages of product design that addresses product families and its generations. The first year of this project saw the development of methodology that promotes design for recycle modularity. The key concepts are as follows.

1) representation of product retirement specification for families and generations
2) evaluation metrics for recycling and reuse modules
3) design tools to promote efficient recycling and reuse

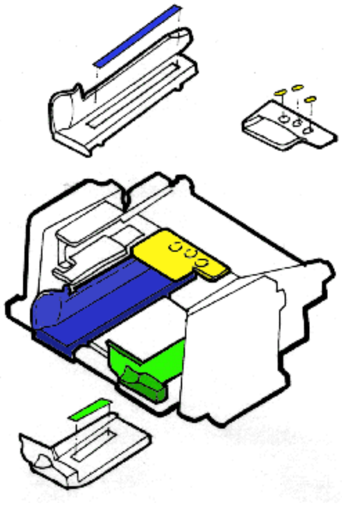
Inkjet printers produced by Hewlett Packard (HP) provided a perfect case study to propel our research. HP manufacturers over 10 different models of the printer, and the models turn over regularly at approximately two year intervals. The printer uses many different materials ranging from commodity plastics to expensive special purpose metal alloys. HP also has a recycling plant near Sacramento that handles all the models and different generations. Student teams in Stanford’s graduate design course ME217 "Design for Manufacturability" used the tools described below and proposed design improvements.

Following section will describe the *reverse fishbone diagram*, a tool we have developed to aid designers make advanced plan for product retirement. Further, the paper proposes the *recyclability maps* a chart that indicates the recyclability of a particular product and recycle process design. The chart combines disassembly and sort complexity as well as material recovery efficiency (scrap rate) and helps designers improve the overall recyclability by appropriate material selection and modularity. The paper closes with current challenges in relating material selection to eventual recovery efficiency and the need for material recyclability database.

ADVANCED PLANNING FOR RECYCLING: THE REVERSE FISHBONE

To encourage design engineers to incorporate recyclability, we have defined the reverse fishbone diagram as a representation of the product retirement process (Ishii and Lee, 1996). Figure 3 shows the current retirement process for a paper tray in the inkjet printer, illustrated in Figure 2. The example is a small part of a larger hierarchical tree for the entire printer. The origin of the diagram is the assembly fishbone diagram, which Stanford uses in documenting the assembly process. Designers can simultaneously address assembly and recyclability using these diagrams.

The size and shape of the tree indicate the complexity and cost associated with the demanufacturing process. The levels or the "length" of the tree indicates the number of different disassembly stations required to process. Nodes indicate the disassembly/separation process. The end nodes indicates "clumps" of parts or materials to be reused or recycled. Generally, smaller tree indicates good design for recycle modularity provided there are demands for clumps to be reused or recycled. Long trees are undesirable, since they indicate many levels of sequence dependent operations. Construction of the diagram forces the designers to "walk through" the demanufacturing steps and aim for efficient recycling process.



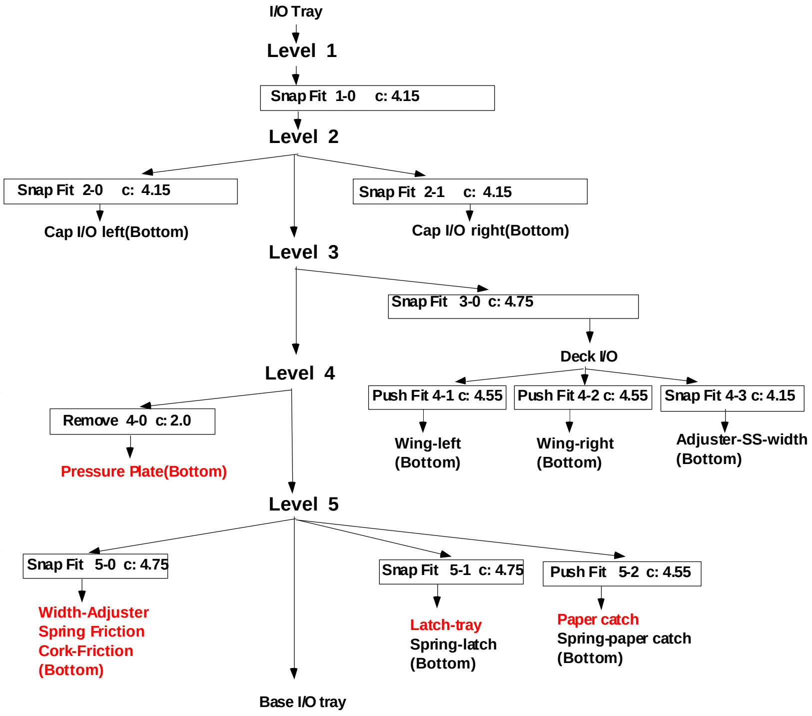


Figure 2: Printer Paper Tray Figure 3: Reverse Fishbone Diagram of the Paper Tray

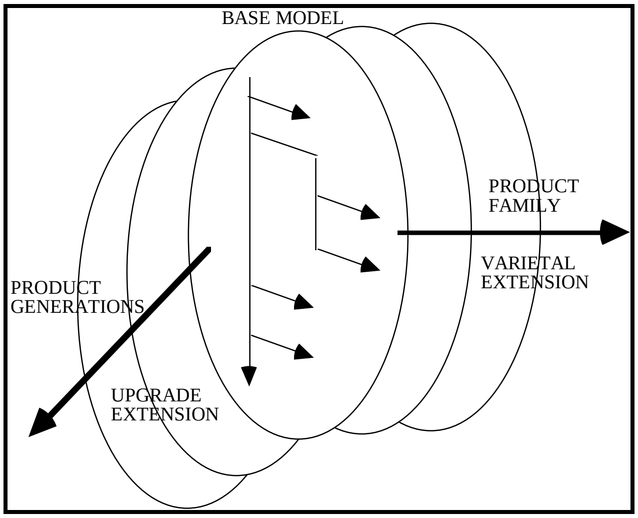


Figure 4: Retirement of Product Families

Whereas the reverse fishbone diagram proved effective in improving the recycle modularity of one product model, it does not address the retirement process of product families and generations. Currently, one must construct the diagram for each product family and generation and compare them to see if a common retirement or demanufacturing facility applies to the entire family and generations (Figure 4). Whereas the diagram helps designers qualitatively simulate the dismantling process, it falls short of helping them generate effective recyclability ideas in material selection and assembly designs for product family. Designers need an efficient way to compare families of trees and seek to commonize the processes.

EVALUATION OF REVERSE FISHBONE: THE RECYCLABILITY MAP

To help designers improve recycle modularity through appropriate material selection and assembly construct, we have proposed several metrics for the complexity of the product demanufacturing process.

1) Variety Complexity: Commonality of parts in a product family. An example metric could be *total number of unique parts* divided by *average number of parts in a product.*
2) Material Complexity: Number of types of materials used in a product.
3) Sort Complexity: Levels of the reverse fishbone diagram and the number of clumps.

This case study revealed that the ***total number of sort bins*** required for a retirement process of a product family is a good overall indicator of all three metrics above. In general, more sort bins indicate deeper levels of disassembly, higher material count, and low commonality. A good design for recycle modularity should lead to fewer sort bins.

As we refine and validate the evaluation measures, we developed design charts that helps designers easily understand the ratings for the current design and identify directions for improvement. Figure 6 shows a candidate chart that plots the number of sort bins against percentage of parts or materials that goes to landfills or incineration process (scrap). The example revealed two classes of “clumps” or subassemblies. The class on the bottom right consists of parts most of which are scraped. Designers must consider different materials or modularity to enhance the reuse and recyclability. The paper (I/O) tray, on the upper left, had a high recovery rate in its original design.

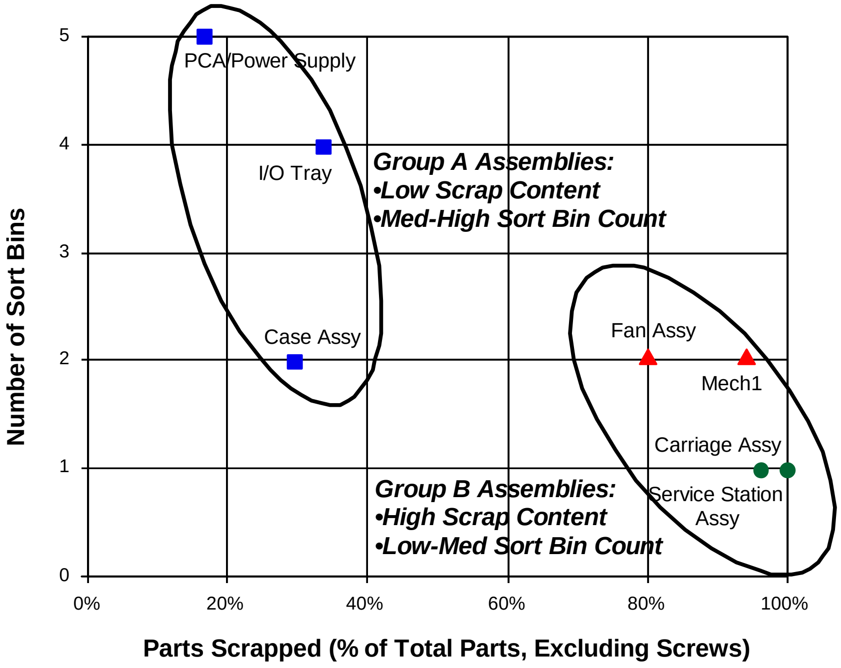


Figure 6. Recyclability Map: a Design Chart

Student teams in ME217 used the recyclability map to redesign the paper tray. They reduced the number of plastic materials from three to one (all ABS), improved the disassembly by changing the fastening methods and reduced the fishbone tree to one level, and thus reduced the number of sort bins from four to three. The result is a 70% decrease in disassembly time and 60 % reduction of scrap (from nearly 40% to less than 20%).

One should note that the student teams had difficulty generating these ideas from reverse fishbone alone. Only after constructing the recyclability map, they were able to focus their effort to key areas of improvement. Thus, the chart can identify focus area of improvement and generate ideas. Generally, the lower left corner is where designers should target. Although the student effort did not address multiple models of printers, the recyclability map can easily accommodate data from the entire model set that the recycling plant processes.

FUTURE CHALLENGES: MATERIAL RECYCLABILITY DATABASE

Whereas the recyclability map (number of sort bins vs. scrap rate) helped in the *redesign* of inkjet printers, the effort required detailed scrap rate information from the recycling plant. Fortunately, HP's Recycling Organization provided with the data for our example. However, how can we apply this tool to a design of a new product for which scrap rate information would not be available. One would have to *estimate* the scrap rate from information associated with *material selection* and *recyclability data* for each set of materials.

Figure 7 shows another design chart that plots the number of sort bins against number of materials contained in each module. Designers can create this chart without the scrap rate information, and thus apply the chart for new product families in their early stages of development. However, comparison of this plot with the *recyclability map* (Figure 6) reveals that the scrap rate is does not always correlate well with the number of materials used in a module. The reasons this mismatch are several:

- Some modules are effectively reused or remanufactured despite the complex material set

- Some modules may contain material sets for which there are economical separation methods
- Some materials may have very low residual value even if recovered cleanly

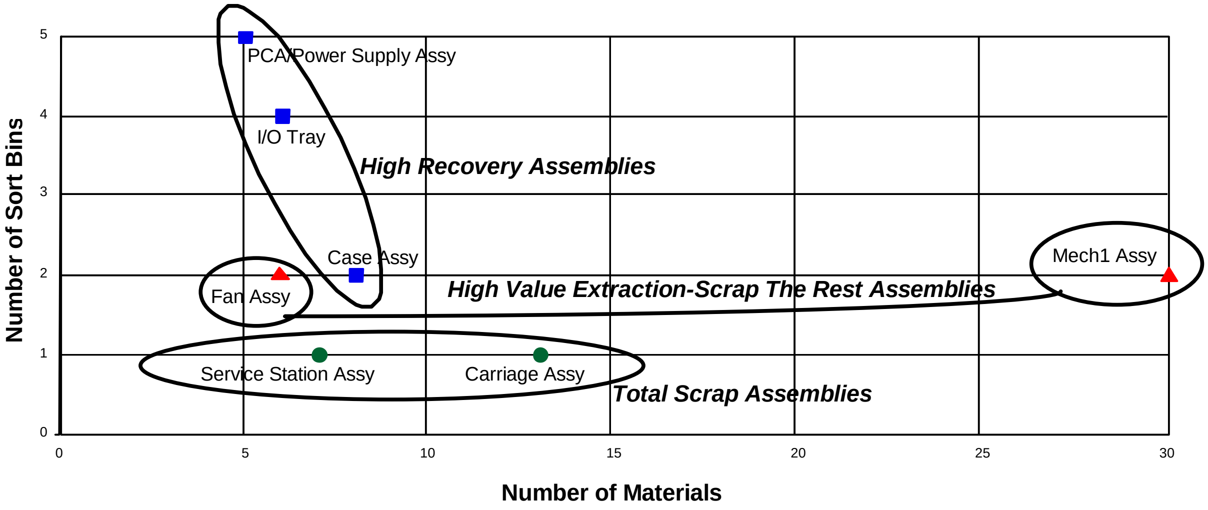


Figure 7. Another Potential Design Chart

Since we are interested in the overall recovery of values from recycled products, either through reuse, remanufacture, or recycling, figure 7 is not as effective as the *recyclability map*. What designers need is database and a method to predict the *scrap rate* given the material selection and post-life intent of each module. Our collaboration with several recycling plant has identified the following factors to be essential:

1. Value of recycled module for reuse or remanufacture
2. Material compatibility (value as a mixed material or ease of separation after grinding)
3. Recycled value of the material recovered

All three changes dynamically from region to region and over time. The second and third factor directly influences material selection for recyclability. Such factors should be a part of a dynamic material database along with other environmental impact such as energy use, resource depletion, and pollution effects. Our future work will focus on the definition of material recyclability database, method to predict scrap rate, and developing an internet-accessible tool for constructing the reverse *fishbone diagram* and the *recyclability map.*

CONCLUSION

This paper presented our on-going work on design for recycle modularity and its implications to material selection. The HP inkjet printer study illustrated the development of *reverse fishbone diagram* as a representation of dismantling process and the *recyclability map* as its evaluation chart. The chart effectively helps designers to focus their effort and to enhance the environmental compatibility of product families and generations. An effective material recyclability database and the prediction of scrap rate will be the key challenge for the future.

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