Proceedings of
The 1997 ASME Design Engineering Technical Conferences and
Computers in Engineering Conference
September 14-17, 1997, Sacramento, California

97-DETC/DFM-4345

ROBUST DESIGN FOR RECYCLABILITY
USING DEMANUFACTURING COMPLEXITY METRICS

Burton H. Lee
Seung Rhee
Kosuke Ishii
Department of Mechanical Engineering
Stanford University
Stanford, California

ABSTRACT

This paper proposes a design chart incorporating demanufacturing complexity metrics in robust design for recyclability. The proposed *recyclability map* relates sort complexity and material recovery efficiency for major subassemblies. The map helps designers to reduce product retirement costs and scrap through the appropriate selection of design modularity, material selection and disassembly strategy. Our method focuses on the dismantling process associated with multiple product families and generations and incorporates changes in recycling process technology capabilities. The recyclability map allows designers to understand the effects of uncertainties in product recycling and helps them to reach a strategy that is insensitive to these changes. The paper uses recycling of an inkjet printer as a validation example.

KEYWORDS: Recyclability, Reusability, Demanuracturing, Modularity, Robustness, Product Families and Generations, Disassembly, Sorting, Material Recovery, Scrap Rate.

1. INTRODUCTION

The recent emphasis on design for environment (DFE; Allenby, 1993) urges designers to include environmental impact along with 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 of a product (SETAC, 1991; US EPA, 1993) from manufacture, to customer use, to eventual disposal. Allenby’s DFE methodology (1993) provides a qualitative evaluation of designs 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. Selection of materials from their life-cycle perspective is a crucial factor influencing product recyclability (Ishii et al., 1994). Common to these design-focused approaches is the notion of concurrent planning for post-life use of the product in the early stages of design, i.e., design for product retirement (DFR; Ishii et al. 1992; Marks, et al. 1993). Implicit in these perspectives is also an assumption of a homogeneous, static and well-known recycling process environment for the product under evaluation. Uncertain external factors outside the control of the designer are not considered in DFR optimality.

This paper takes the viewpoint of demanufacturing plants or recycling organizations (Figure 1) that necessitates a system-wide consideration of product recycling process technologies and economics. From this perspective, the product recycling and retirement process appears highly uncertain and variable. Many factors make effective advance planning for product retirement extremely difficult:

- advancing recycling process technologies
- geographical disparities in product recycling processes
- great variability in retirement timing
- market fluctuations for recycled materials

Not only must the recycling organization consider the recyclability of entire product lines and families, they also frequently handle multiple generations of products from any stage of the supply chain (Ishii et al., 1995). In some cases, the recycling organization may have to process products from different manufacturers. Current DFE methods fall short in accounting for these and other external uncontrollable factors.

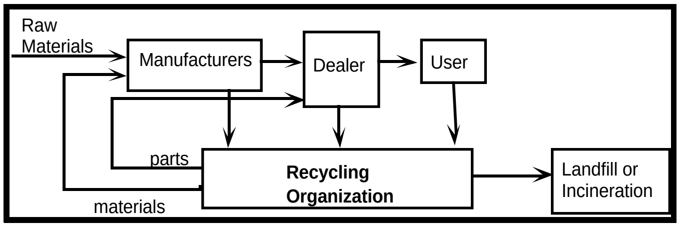

Figure 1: Recycling Viewpoint in Life-cycle Design

A robust approach to design for recyclability is needed to take parameter variations, uncertainties and noise factors into account when evaluating design alternatives. We propose a new framework that categorizes and describes the major recyclability factors in terms of product-independent and product-dependent complexity and uncertainty. The *recyclability map*, a chart indicating the recyclability of a particular product and its constituent modules under a given recycle process, provides a graphical method for performing robust DFR. The chart combines sort and disassembly complexity metrics, as well as material recovery efficiency (scrap rate), helping designers improve product recyclability through appropriate material selection and modularity. The map framework supports robust DFR under product-independent uncertainty, and is intended for application in the early design phase. We close with a case study of a Hewlett Packard (HP) inkjet printer conducted by a student team in Stanford's graduate design course ME217 "Design for Manufacturability." This example application demonstrates concurrent use of the recyclability map and the *reverse fishbone diagram* methodology (Ishii and Lee, 1996) to generate and verify recyclability improvements of individual subassemblies and modules. The reverse fishbone is a tool developed in the first year of this project that promotes design for recycle modularity and aids designers in optimizing designs for product disassembly.

2. ROBUST DESIGN FOR RECYCLABILITY

2.1 Product Retirement under Uncertainty

Design for robustness emphasizes the importance of taking uncertainties into account during product development. The goal is to make decisions such that the product design is least sensitive to variations in uncontrollable factors or noise. Robust Design for Recyclability (RDFR) requires designers to make the environmental friendliness of their product relatively independent of uncontrollable factors. Product-independent variables involve the external end-of-life environment that affects the product's recyclability. The level of recycling process technology and corporate parts reuse policies are examples of uncertainties common to many products. Controllable design factors are those that the designer can fully determine during the design phase such as material selection and design configuration. Three important sources of uncontrollable factors encountered by product designers are the absence of design data, timing of product retirement, and recycling process technologies. Other uncertain factors such as regulations, industrial standards, and product-line architecture can also significantly impact configuration and materials selection decisions.

2.2 Design for Disassembly under Uncertainty

Current recyclability analysis methods depend heavily on, and thus are sensitive to, recycling data. Our work with product designers has consistently revealed concern and frustration over increasingly stringent recyclability requirements in lieu of pertinent data such as:

- future process costs for disassembly and sorting
- material compatibility, processing cost, demand, value.

Typically, when such data become available, it is too late in the design. Where available, the data is often expensive and difficult to use. Because the disassembly process occurs in the future at many diverse locations, it can be difficult to design to known disassembly processes and costs. The absence of adequate data introduces a high level of uncertainty whether a particular design is optimal or sub-optimal from a recyclability perspective. Robust design for recyclability methods should ideally be able to generate useful metrics with minimal data collection and analysis.

2.3 Timing of Product Retirement

Available literature on product retirement assumes that products are retired exclusively near the end of their useful life, when the customer upgrades or discards the item. However, our work with major consumer products manufacturers has revealed that the timing of product retirement is highly uncertain, because it can occur at *any* point in the product life cycle. In one recent case study performed at Hewlett Packard, we discovered that several printer products are retired within weeks of their manufacture due to excess retail inventories, customer returns, and excess wholesale stocks returned directly to the manufacturer for disposal, reconditioning or spare parts extraction. Recycling facilities, therefore, increasingly perform full or partial disassembly of relatively new, unused products, together with disassembly of older used products at the end of their useful life. Thus, the timing of recycling operations can vary greatly for some products and is a new important source of uncertainty for the designer.

2.4 Recycling and Technology Changes

The sophistication of recycling technology varies across geographic boundaries, between recycling organizations, and over time. A single product model can be subject to a range of recycling processes in multiple country markets. Our work has illustrated how the sophistication of available recycling technologies plays a significant role in the level of product disassembly and sorting. The degree to which a particular recycling process can handle different types of plastics dictates the level to which plastics must be separated for color, filler content, and other characteristics. Table 1 describes the different levels of recycling associated with technology to dismantle and process the materials. Note that material compatibility depends on the availability and separation and processing technologies.

Table 1. Technology Levels of Recycling

	Recycling Technology	**Description**	**Disassembly and Sorting**
1	Unsophisticated recycling	Each part is sorted into its own bin	Maximum disassy and sorting High cost process
2	Function-based recycling	Combine similar parts into the same sort bin, based on part function	Intermediate disassembly and sorting
3	Material-based recycling	Each material is sorted into its own sort bin, regardless of part function	Intermediate disassembly and sorting
4	Material family recycling	Combine some different materials into the same sort bins	Minimum disassembly and sorting required
5	Advanced recycling technology	Combine all materials into one sort bin	No disassembly or sorting required Lowest cost process

2.5 Disassembly Reverse Fishbone Diagram

To encourage design engineers to incorporate recyclability, we have defined the reverse fishbone diagram (RFD) as a graphical representation of the product disassembly process (Ishii and Lee, 1996). The origin of the diagram is the assembly fishbone diagram that Stanford uses in documenting the assembly process. Designers can simultaneously address assembly and recyclability using these diagrams. The size and shape of the reverse fishbone tree indicate the complexity and cost associated with the demanufacturing process. Construction of the diagram forces the designers to "walk through" the demanufacturing steps and aim for an efficient process. Currently, one must construct the diagram for each product model and compare them to see if a common retirement or demanufacturing facility applies to the entire family and generations.

Figure 2 is an example of a reverse fishbone diagram for a paper tray of inkjet printers. The boxes indicate the type of operation required to remove components. Detached components are listed below their corresponding disassembly operation. Thus, disassembly efficiency increases as the numbers of components increase under each disassembly operation. Material properties for each component and its fate are described inside the parenthesis. The number of "Levels" indicates how difficult or deep the disassembly process is. An optimal reverse fishbone diagram should be short and wide.

The reverse fishbone diagram helps designers qualitatively simulate the dismantling process and improve the recycling process for a product. However, the diagram falls short of helping designers generate ideas to improve the recyclability at any given demanfacturing facility with certain capabilities. The next section introduces the recycling complexity metrics aimed at evaluating designs for robust recyclability.

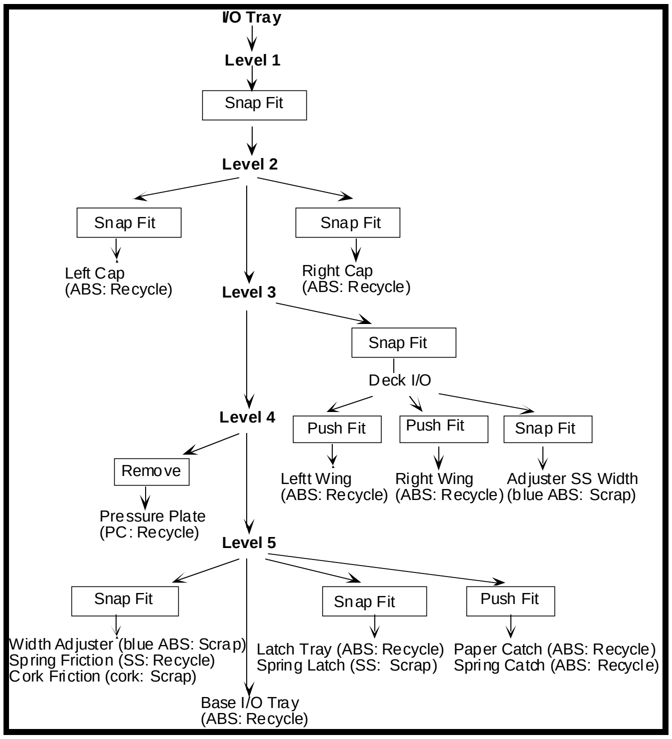

Figure 2. Reverse Fishbone Diagram (RFD) for Inkjet Printer Paper Tray

3. COMPLEXITY METRICS

3.1 Sort Complexity (SC)

Sort Complexity (SC) captures information about the difficulty and cost of the disassembly process as influenced by the following design-independent, product-external factors:

- Level of Recycling Technology Employed
- Level of Product Reuse/Re-manufacture

The sort complexity strongly influences the level of disassembly required when recycling or reusing a product. High sort complexity entails greater disassembly costs and therefore the designer must pay greater attention to disassembly and materials complexity. Thus, the concept of sort complexity captures several important characteristics of the corporate recycling process and can assist the firm in planning product DFE in context of the larger recycling technology and corporate parts reuse policy.

Our principal sort complexity metric is "number of sort bins," where the sort bins are defined as any distinct end fate or destination for a product, module, subassembly or component. Advantages of the sort bin metric are that it is easy to understand and readily estimated by the recycling organization. When considered in the context of the reverse fishbone diagram, the number of sort bins corresponds to the number of different destinations for all the leaves on the diagram. 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 for a given level of recycling process technology employed.

We assume that a particular product can be sorted into one to many sort bins. A highly sophisticated recycling technology ("Process Level 5," Table 1) should be able to "sort" the product into only one bin, since the recycling process is capable of taking in multiple materials and processing them. On the other hand, sending the entire product to scrap constitutes a single sort bin. We assume that the "scrap" bin is least desirable among all possible sort bins because it is environmentally most harmful (requiring landfill or incineration). As explained above, the sort complexity (SC) is a function of two major factors: disassembly (separation) and "clump" processing. The following sections propose metrics to capture these two factors.

3.2 Material Complexity (MC)

Materials complexity (MC) is determined during the design phase and plays an important role in determining disassembly decisions and total recycling cost. Materials complexity is relevant because the recycling technology is constrained in its ability to process all materials together. Essentially, material complexity refers to the number of materials used in a component, subassembly, or product.

Number of Material Classes: Broadly, we can group materials into the following categories: plastics, ferrous and non-ferrous metals, paper and wood, hazardous materials, other. The number of different material classes has a strong influence on the materials complexity of product components and assemblies.

Materials Compatibility: Some combinations of materials may not be processed together during recycling. This is a strong function of the current level of recycling technology, as mentioned before.

Special Handling. Certain materials are difficult and/or very costly to handle, possibly requiring special equipment (separate room, container, suit, etc.).

Relative Valuation of Materials. For simplicity, we assume here that all materials are broadly equivalent in "goodness" or "badness" ranking from an environmental perspective. The materials complexity metric does not reward or penalize particular material classes, or materials, selected by the designer.

3.3 Disassembly Complexity (DC)

While material complexity focuses on the processing cost of "clumps" after separation, disassembly complexity (DC) addresses the cost of disassembly and separation of the product into these "clumps." Obviously, the total disassembly cost is heavily related to the number of sort bins. However, DC is also dependent on the product design and the disassembly technology employed. Designers should provide for easy disassembly of each "clump" depending on its fate. Re-use clumps require easy non-destructive disassembly, whereas clumps to be ground allow for destruction of fasteners and the clumps themselves.

4. THE RECYCLABILITY MAP

4.1 Basics of the Map

The recyclability map is a design chart for the early identification of modularity and disassembly strategies leading to significant reductions in recycling costs. The map can be used both as a global system-level tool to monitor and compare recyclability improvements across product families and generations, and as a subsystem-level guide to component-specific redesigns for an individual product. The map is a companion tool of the reverse fishbone diagram in promoting a robust approach to advance planning of the disassembly and sorting process under uncertainty. It is most useful during the layout design phase, when alternate materials and configurations are under consideration. The map also supports design trade-offs and redesigns for individual subassemblies performed over the history of a product platform.

The recyclability map derives its analytical power from the unique use of simple sort complexity ratings and material recovery efficiencies. Combining these metrics into an intuitive graphical representation facilitates quick trade-off analysis for design improvements at the subassembly and major component level, without placing heavy burdens on the designer for extensive data analysis. Combining both product-dependent and design-independent metrics brings an important benefit: robust design-for-recyclability. Sort bin count models the effect of alternative recycling technologies and processes. The map allows designers to roughly compare a single design under alternative recycling process technology assumptions.

4.2 Information Required to Construct the Map

Construction of the recyclability map (Figure 3) requires layout design information and recyclability assessments by designers and recycling experts. First, the "fate" of major subassemblies and components must be identified. This step requires prioritization of product maintenance, parts reuse, recycling and regulatory compliance goals by designers and other involved parties. Analysis of product service and tear-down reports is one method of assessing part fates using historical data for a product family. The boundaries between regions in figure 2 are conceptual and subject to product and industry characteristics.

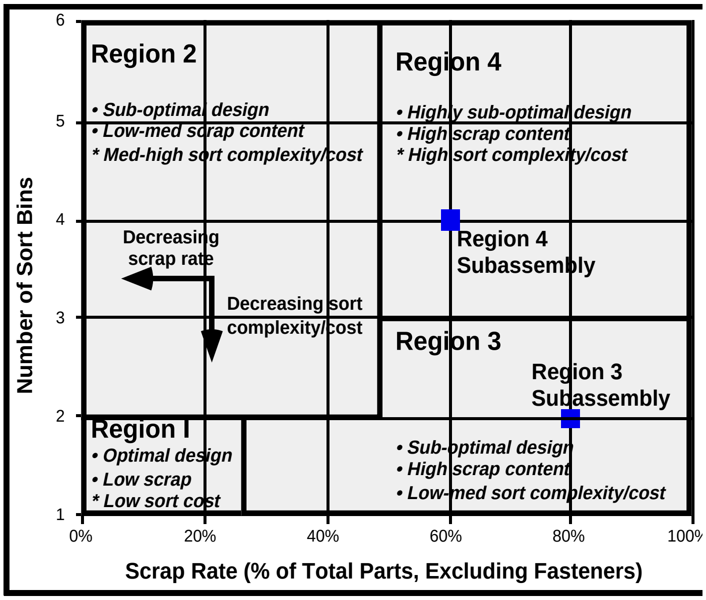

Figure 3: Recyclability Map and its Regions

Next, one must estimate scrap rates for each module based on the percentage of total parts sent to scrap, i.e., to a landfill. A low scrap rate is preferable indicating a high degree of materials recovered from the module. Our initial work adopted equal weighting to all parts in a module by using part counts; simple fasteners are excluded from part counts as they can bias certain classes of subassemblies towards the left side of the map, depending on the type of fastener material employed. Refinements of the scrap rate metric are under consideration.

The recycling organization assesses the sort complexity of a proposed design (Y-axis data), based on preliminary materials content and configuration choices made by the design team. For each module, major component or subassembly, the recycling organization identifies the total number of sort bins required after tear-down, removal, and disassembly. A high sort bin count is less desirable because of the increased cost of disassembly and sorting required. Thus, sort bin count serves as a proxy metric for disassembly and sort cost. The sort bin count may vary significantly, depending on the particular recycling process technology and regulatory environment.

Successful use of the recyclability map necessitates early communication between the designer and recycling organization. Thus, an understanding of the disassembly and sorting process, as well as the range of possible recycling process technologies that are likely to be employed, is essential.

4.3 Construction of the Recyclability Map

Knowing the intended fate of each part, the designer generates the recyclability map for the complete, integral product, including all subassemblies where data is sufficient to permit useful qualitative analysis. For each subassembly, its position is plotted against the map X- and Y-axes, keeping in mind the level of uncertainty in the supporting scrap rate and sort complexity data. The number of sort bins is determined by

SC that is dependent on the sophistication level of the recycling process to be used. The scrap rate depends on the material complexity (MC) and demand for the recovered material, and may change due to advancements in recycling technology.

If the current design is an iteration or version within a product family or generation, the designer may estimate X-Y coordinates on the current map starting with existing recyclability maps for related products using similar modules. As the design progresses, the map should be updated to reflect design tradeoffs and subassembly redesigns performed. Once directions for improvements to a particular subassembly have been set, the reverse fishbone diagram can help designers to quantitatively verify reductions in disassembly times and sort bin count. Design improvements may shift the subassembly to a new location on the map. Thus, the designer can iterate back and forth between the reverse fishbone and the map, using the map both as a global system-level tool to monitor recyclability improvements and as a subsystem-level guide to specific redesign changes. Analysis of product service and tear-down reports is necessary to identify the "fate" of major components, i.e., their final destination after tear-down, removal, and sorting (c.f. Table 1). From the service perspective, the reverse fishbone is a good starting point for targeting which items to keep for later use; other items are sorted into other fate categories, depending on recycling market or regulatory incentives.

Many parts need not be removed in the disassembly process. This notion differentiates our reverse fishbone diagram from other research that focuses solely on disassembly. Parts that remain in the product shell end up in the fate category “System Grind.” Depending on the product, this category can be a major portion of the product.

4.4 Analysis and Interpretation of the Map

Qualitative analysis and interpretation of the recyclability map require an understanding of how the map *regions*, subassembly *redesign paths* and *redesign costs* relate to the available design alternatives. Given a fixed recycling technology environment, the initial location of a subassembly on the map suggests directions for possible design improvements in material choice and disassembly strategy. Design improvements will move subassemblies from one region to another along one or more trajectories. Depending on the circumstances, movement along different trajectories between regions results from reducing or increasing material, disassembly, and/or sort complexity.

Region 1, characterized by low scrap rate and low disassembly/sort cost, is optimal for all subassemblies. Ideally, all subassemblies should fall in - or move towards - this region. Under ideal recycling technology and design, the product does not need to be disassembled and sorted at all, such that only one or two sort bins are required, with full material recovery. In practice, however, Region 1 is very difficult and costly to attain.

Region 4 is highly undesireable for all subassemblies. Subassemblies of this type have a high scrap rate and high disassembly and sorting costs. Improvements can be made to Region 4 subassemblies by either reducing the scrap rate (moving to the left, towards Region 2), reducing the sort bin count (moving down towards Region 3), or by doing both (moving diagonally towards Region 1). Moving a subassembly towards Region 2 is essentially a materials selection decision; moving down towards Region 3 implies easier disassembly, a reduction in the number of materials, or changing to a more sophisticated recycling technology process.

Table 2: Regions of the Recyclability Map

	Recyclability Characteristic	**Design Optimality**	**Designer Actions**
1	High material recovery rate Low disassembly and sort costs	Optimal design Zero penalty	Move all subassys towards this region, via Region 2
2	Medium-low material recovery rate High disassembly and sort costs	Sub-optimal design Moderate penalty	Move subassemblies towards Region I Move away from Region 4
3	Low material recovery rate Low disassembly and sort costs	Sub-optimal design Moderate penalty	Move subassemblies towards Region 2, and if possible, towards Region I Move away from Region 4
4	Low material recovery rate High disassembly and sort costs	Highly sub optimal design Large penalty	Move all subassemblies out of, and away from, this region

Most product subassemblies typically fall into Region 2 or Region 3. Region 2 subassemblies, already have low scrap rates and high recovery of material. The recyclability of these subassemblies can be improved through further increases in the recovery rate (move to the left) and/or reduction in sort complexity and cost (move down). Region 3 is where many subassemblies begin. Subassemblies in this region are characterized by low material recovery rates and low sort complexity and cost. Ideally, Region 3 subassemblies should seek to move directly towards Region 1; in practice, however, they will typically move first towards Region 2, since the available recycling process technology is not sophisticated enough.

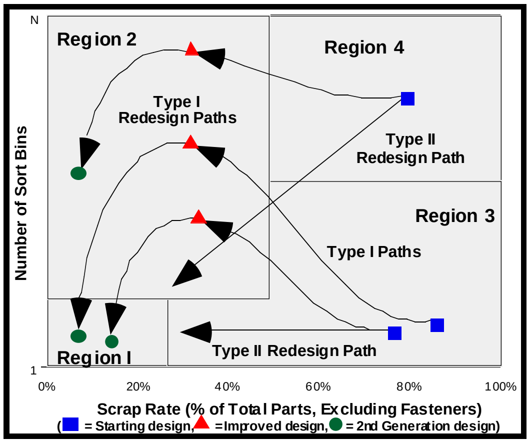

Figure 4: Redesign Paths for Subassemblies

As a rule, the designer should initially target design improvements on subassemblies in Regions 3 and 4. Gains to be made from design improvements to these subassemblies are likely to be substantial compared to Region 2 subassemblies.

Type I redesign paths (Figure 4) move a subassembly through Region 2 before moving to Region 1. These paths are typically easier to achieve within a typical design project, and are less costly than Type II paths. Type II redesign paths move a subassembly from its current design region directly towards Region 1. These paths are costly, and as such are difficult to achieve for a single product. Successive generations within a product family, however, might gradually pursue a Type II trajectory over several redesign generations.

Table 3: Classes of Redesign Paths

Path	Characteristics	Feasibility & Cost
Type I	Redesign for Region 2 in short term Target Region 1 over successive product generations	Incremental redesign Easier to achieve for single models Low-moderate cost redesign
Type II	Redesign for Region 1	Major redesign required Difficult to achieve within a single product generation Higher cost redesign strategy

4.5 Product Families and the Recyclability Map

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. The recyclability map is an efficient quantitative tool for comparing and monitoring incremental DFR improvements over time.

Currently, one must construct the reverse fishbone 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 7).

5. APPLICATION EXAMPLE

5.1 Analysis of an Inkjet Printer

Inkjet printers produced by Hewlett Packard (HP) provided an appropriate case study to propel our development of the recyclability map concept. HP manufactures 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 thermoplastics to expensive special purpose metal alloys. HP has a product retirement facility in Northern California, the Hardware Recycling Organization, that disassembles, sorts and recycles all printer models, including older generations, and with whom we worked closely during the validation phase of our research.

A graduate student team in Stanford's ME217 Design for Manufacturability course developed the recyclability map to redesign the printer paper (I/O) tray and ink spittoon for a Hewlett Packard 855C Deskjet Printer (Figure 5). Figure 4 shows a chart that plots the number of sort bins against percentage of parts or materials that go to landfills or the incineration process (scrap). The example revealed two classes of “clumps” or subassemblies. The class on the bottom right (Group B assemblies, Region 3) consisted mainly of parts to be scrapped. Designers must consider different materials or modularity to enhance the reuse and recyclability. The paper tray, on the upper left (Group A assemblies in Region 2), had a high recovery rate in its original design. Here, the redesign goal is to reduce sort bin count and improve material recovery through appropriate material selection (figures 7 and 8).

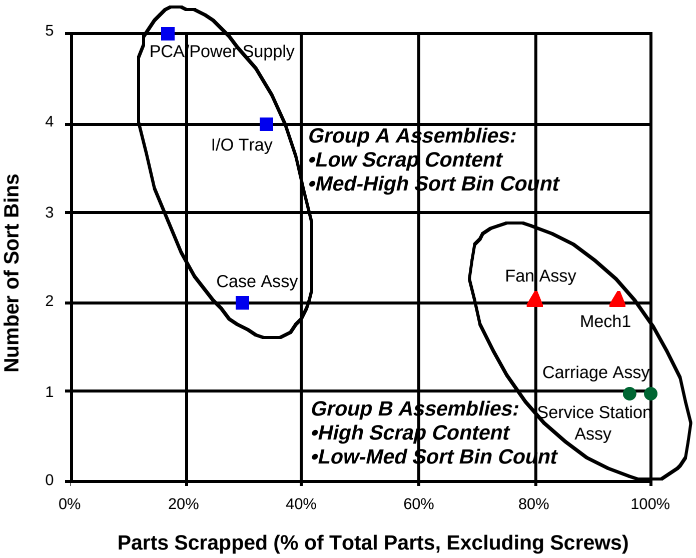

Figure 5: Recyclability Map of an Inkjet Printer

For the I/O tray (see Figure 6), a Region 2 subassembly, the map pointed to possible redesign improvements through reductions in scrap rate and sort complexity (see Figure 7). They reduced the number of plastic materials from three to one (all ABS), and improved the disassembly process by changing the fastening methods and reducing the reverse fishbone to one level. The result is a reduction in the number of sort bins from four to three and a 50% reduction of scrap (from nearly 35% to less than 15%), based on part count.

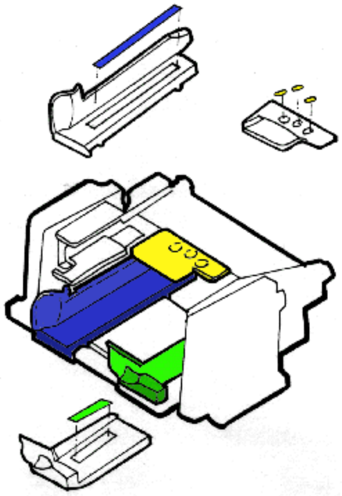

Figure 6: Printer I/O Paper Tray

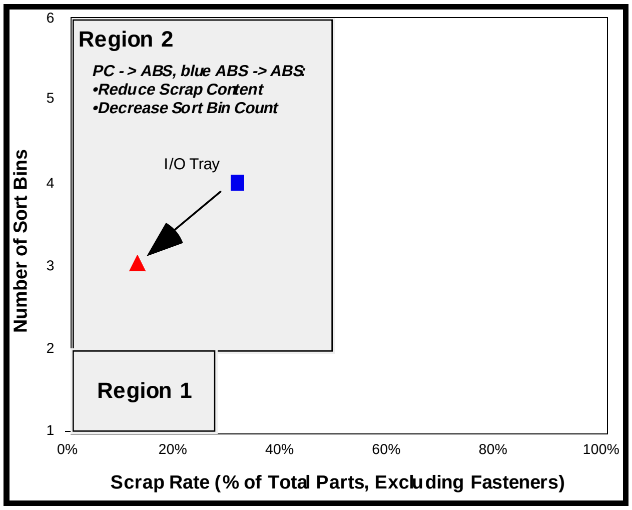

Figure 7: Redesign Path for Printer I/O Tray

The proposed design also leads to a drastically simplified disassembly process as shown by the reverse fishbone diagram (figure 8). Note that the original design resulted in a much more complex reverse fishbone diagram (c.f. figure 2). The new diagram leads to a 70% reduction in assembly time.

At an early point in the project, and with relatively little data on hand, the chart successfully identified areas of improvement and generated specific materials selection ideas. One should note that the student teams had difficulty generating these ideas from the reverse fishbone diagram alone. The cooperation of the HP Hardware Recycling Organization was essential to the success of this effort, and illustrated the benefits of early communication between the design team and recycling experts.

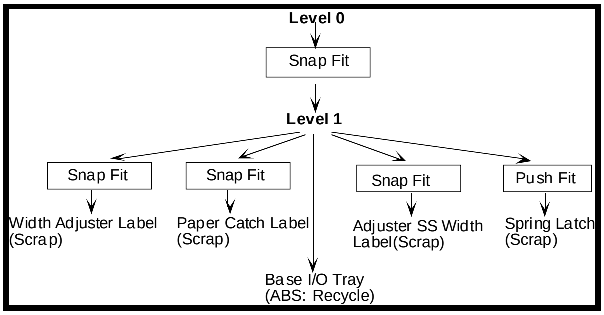

Figure 8: RFD of Proposed Design

5.2 Limitations of the Recyclability Map

Similar to other DFM tools, the utility of the recyclability map depends on the data available to the designers, and the extent of analysis required. Successful use of the map depends on prior knowledge of the fate of all parts for each subassembly analyzed. Some companies have developed lists of parts that they will stock for their maintenance programs. For other components, the company separates only high value components or materials for recycling and the rest is left as carcass. Understanding the current and projected market demand for parts reuse and recycling is essential to discriminate between what deserves focus and what should be ignored. In the worst case, the designers should consider all reusable parts as candidates for removal.

In its current form, the recyclability map assumes equal weightings are assigned to all sort bins, parts and functional modules. This has the advantage of simplicity, but may introduce distortions into the model that could be corrected through differential weightings. Our current sort complexity approach explicitly assumes that most sort bins are approximately equally desirable, i.e., we do not ascribe formal penalties or weightings to particular bin classes. Where particular materials require special, costly handling, for example, such as toxic or radioactive materials, those sort bins should probably receive cost or environmental penalty weights, while other "normal" sort bins can be ranked equivalently.

We have also assigned equal weighting to all parts in a module by using part counts; thus a spring and plastic housing are considered equivalent in this scheme. Weightings by mass, volume and/or material type/class might prove more accurate. Simple fasteners are excluded (i.e., weighting = 0) from part counts, as they can bias certain classes of subassemblies towards the left side of the map, depending on the type of fastener material employed. Functional modules are equally weighted as well; electro-mechanical assemblies and static load-bearing structures such as housings are counted equivalently here. This may make comparisons between subassemblies more difficult.

The utility of the recyclability map is its construction and use as trade-off analysis and design review tool. The great benefit of the diagram lies in its additional motivation to bring together recycling organizations, designers and other parties responsible for the environmental impact of a product.

6. CONCLUSION

This paper introduced the recyclability map as a new graphical design tool for the early identification of product subassemblies where appropriate material selection and disassembly redesigns can increase material recovery efficiency and reduce retirement costs. We began with a brief description of our previous work in developing the disassembly reverse fishbone diagram as a representation of the dismantling process. The paper then gave a detailed description of the recyclability map, its definition and construction, and how it is used together with the reverse fishbone to perform DFR tradeoff evaluations. The HP inkjet printer study illustrated the practical application of the recyclability map.

The map helps designers to focus their efforts during the early design phase, and to enhance the environmental compatibility of individual subassemblies and components, as well as extended product generations and families. The map can be used both as a global system-level tool to monitor and compare recyclability improvements across the full product design, and as a subsystem-level guide to component-specific redesign changes. It facilitates cross-generational and model-to-model comparisons within product families, providing a common basis for advance planning of incremental product redesigns aimed at improved recyclability over time.

While still in its infancy of development, early feedback from industry indicates that the use of recyclability map is effective in the following DFR tasks:

- Early identification of recyclability improvements at the subassembly level
- Advance planning and tracking of DFR improvements in product families over several generations
- Robust design for recyclability under uncertainty

- Assessment of product designs under alternative recycling process technology environments

The diagram can be employed as the basis for a collaborative design review and communication tool between design and manufacturing divisions and recycling organizations. Improved coordination of design projects with other activities in the organization and its supply chain is vital to optimizing product modularity not only for manufacturing and service, but also for product retirement impacts.

ACKNOWLEDGMENTS

Funding for this research comes from the National Science Foundation Environmentally Conscious Manufacturing Grant DMI-9528615 and the Lucent Foundation Industrial Ecology Faculty Fellowship. The authors would like to thank Hewlett Packard for their assistance in the student design project described in the paper. Members of the student project team included Heecheol Jeon, Sanjay Rajagopalan and Burton Lee.

REFERENCES

Allenby, B.R. (1991) “Design for Environment: A Tool Whose Time Has Come.” SSA Journal, September, 1991, pp. 5-10.

Beitz, W. (1993) “Designing for Ease of Recycling--General Approach and Industrial Applications.” The ninth International Conference on Engineering Design (ICED), August, 1993, The Hague, Netherlands, pp. 325-332.

Hattori, M., and Inoue, H. (1993), "Concept of Ecofactory," Proc. of the 1993 IEEE/Tsukuba International Workshop on Advanced Robotics, Tsukuba, Japan, November, 1993, pp. 3-8.

Ishii, K., Eubanks, C.F., Marks, M. (1992) Evaluation Methodology for Post-Manufacturing Issues in Life-cycle Design, *Concurrent Engineering: Research and Applications*. Vol. 1, pp. 61-68.

Ishii, K., Eubanks, C., and Di Marco, P. (1994), "Design for Product Retirement and Material Life-cycle." Materials and Design. Vol. 15, No. 4, pp. 225-233.

Ishii, K., Lee, B., and Eubanks, C. (1995) “Design for Product Retirement and Modularity Based on Technology Life Cycle,” 1995 ASME Winter Annual Meeting Symposium on Life Cycle Engineering, Nov., 1995, San Francisco, CA. ASME MED-Vol. 2.2, pp. 921-933.

Ishii, K. and Lee, B. (1996) " “Reverse Fishbone Diagram: A Tool in Aid of Design for Product Retirement,” ASME Design Technical Conference, Aug., 1996, Irvine, CA. ASME Paper 96-DETC/DFM-1272.

Jeon, H., Lee, B. and Rajagopalan, S. (1996) "HP 855C Color Deskjet Printer: Design for Environment, Design for Service,” Final Report for Course ME 217B, Department of Mechanical Engineering, Stanford University, Spring Quarter 1996.

Marks, M., Eubanks, C., and Ishii, K. (1993), "Life-Cycle Clumping of Product Designs for Ownership and Retirement." Proc. of the ASME Design Theory and Methodology Conference, Albuquerque, New Mexico. ASME DE-Vol. 53.

Society of Environmental Toxicology and Chemistry (SETAC) (1991) “A Technical Framework for Life-Cycle Assessments”, January, 1991, Washington, D.C.

U.S. Environmental Protection Agency (1993) "Life-Cycle Assessment: Inventory Guidelines and Principles", EPA Report No. EPA/600/R-92/245, Office of Research and Development, Washington, D.C.