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Final Report on Design of Recyclable Products

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Enhanced Recycling, Action Plan 2000 on Climate Change, Minerals and Metals Program — *The Government of Canada Action Plan 2000 on Climate Change Minerals and Metals Program, managed by the Minerals and Metals Sector of Natural Resources Canada, is working towards reducing Canada's greenhouse gas (GHG) emissions from the minerals and metals sector. By matching funds with other partners, this program supports initiatives that enhance recycling practices and provide GHG emission reductions.*

Canada

DISCLAIMER

FINAL REPORT ON DESIGN OF RECYCLABLE PRODUCTS

by

S. Bell[*], B. Davis*, A. Javaid[**] and E. Essadiqi**

EXECUTIVE SUMMARY

Over the last few decades, enormous social and political pressure has been placed on consumer goods manufacturers to take the environment into consideration when designing new products and/or processes. The majority of this pressure has been due to the realization that many products have an adverse affect on the environment during their production, use, or disposal. For example, studies have estimated that over 14 million tonnes of plastics are being landfilled each year in the U.S. alone.

Because of these environmental concerns, several initiatives have been undertaken to tie together the ecology and product design to lessen the burden of consumer goods on the environment. One such program is entitled 'Design for Recycling' (DfR), which has gained popularity in the European Union (EU) because of a lack of landfill space and dwindling local sources of raw materials.

The overall goal of the DfR initiative is to increase the overall recyclability of consumer products, and subsequently reduce the amount of landfilling, by:

1. minimizing the variety of materials and parts,
2. avoiding the use of harmful materials, and
3. making the disassembly of various parts and dissimilar materials easier.

In order for this goal to be achieved, recycling must play a larger role in product design. However, a better understanding of the various aspects of recycling – including a product's life cycle, modes of recycling, material selection, and disassembly technologies – needs to be gained before a successful DfR can be performed.

A product's life cycle consists of four distinct stages that encompass the design, production, use, and end-of-life phases. The term 'demanufacture' is becoming more popular for describing the process or processes employed in recycling products and materials and is sometimes used to describe a portion of the end-of-life phase.

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There are various options available for recycling a product, including re-use or re-manufacture, material recycling, and energy recovery. Re-use or remanufacture applies to products that have been recovered from a waste stream and are to be used again in their original application. On the other hand, material recycling refers to the recovery of materials from a solid waste stream for use as raw material in the production of new goods. Lastly, materials that are incinerated (mostly plastics) for a source of energy fall under the category of energy recovery or energy recycling. Energy-recovery systems are used mostly in the EU and are considered an adequate recycling option. In terms of recycling priority, re-use or remanufacture is preferred since all of the energy that originally went into the production of the good is conserved.

Proper material selection is absolutely essential for a successful DfR since non-compatible materials are the leading factor that makes recycling impossible or uneconomical. To increase the recyclability of a product, regulated and/or restricted materials should not be chosen, all materials should be completely recyclable, the number of different materials within the product should be reduced, and surface coatings should be minimized. In addition, different types of plastics should be properly marked for easier identification during manual disassembly.

Disassembly, through either non-destructive or destructive techniques, plays a major role in improving the recyclability of a product. In order to make non-destructive disassembly (manual) easier, the number of fasteners should be reduced, similar fastener types should be used, the fastener material should be compatible with the body of the product, and snap-fits should be utilized wherever possible. All these factors work together to make the recycling operation more economical by increasing the number of parts removed for re-use (higher valued items) and reducing the amount of labour.

In destructive disassembly systems, the focus shifts back to material compatibility since the fasteners will not be unfastened which makes disassembly time irrelevant. If compatible materials cannot be used throughout the part, materials with very dissimilar properties should be used to make common separation practices (magnetic, sink float, eddy current, etc.) easier and more effective in producing an uncontaminated feed stream for recycling.

Various DfR guidelines have been developed by a variety of institutions, public and private, to aid companies in implementing DfR into their design process. ARCELOR, a majority steel scrap recycler in France, devised a four-stage DfR approach for metals (mostly steel). In addition, the EU laid out an approach for manufacturers to use in order to determine the correct metal to non-metal ratio in their product(s). This was of great importance because of the EU’s regulation on recycling, which mandates that all automobiles must be at least 85% recyclable by 2006 and 95% by 2015. Moreover, the US Vehicle Recycling Partnership devised and recommended an industry-wide recyclability assessment method for DfR based on a simple but effective rating system.

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INTRODUCTION

Almost all of the products manufactured today have some adverse affects on the environment. For example, automobiles burn gasoline or diesel to run which, in turn, pollutes the environment with, among other things, green-house gas (GHG) emissions. New electronics require the use of very special metals that have negative effects on humans, wildlife and vegetation when they enter water streams from either initial production or improper disposal.

Because of increasing public awareness of environmental issues, governments have been forced to implement more strict environmental policies. The most recent example of this is the Kyoto Protocol – an initiative of more than 160 countries to reduce GHG emissions. Canada's target is to reduce GHG emissions by 6% from levels previously recorded in 1990, between 2008 and 2012[1]. This reduction is in agreement with the actions taken by other large industrial nations, such as the United States (U.S.).

Environmental policies have caused manufactures to take note of the environmental impacts created by not only their production process but also their product over its entire life cycle. Subsequently, this has spurred the development of various programs, from both the government and individual manufacturers, to consider the environment when designing a product and processing stream. In addition to government policies, there are numerous other reasons for a manufacturer to adopt an environmental design program. One such example is the direct link between environmental effects and inefficiency and waste. The latter is further tied to a reduction in productivity and greater liabilities (i.e., human health), both of which result in some businesses decreased revenues. In addition, some businesses are starting to require their suppliers to have an Environmental Management System (EMS) in place that is inline with ISO standard 14001. The 14000 series standards are focused solely on environmental-management issues that minimize the negative effects of a manufacturer's activities on the environment. This standard outlines regulations and guidelines that management systems are intended to follow[2]. For example, General Motors (GM) and Ford are now requiring EMS from all their suppliers. This has caused a ripple effect through the automobile supply chain, requiring organizations to fully grasp the life cycle of their product(s) so that they can comply with their customers' demands and remain future suppliers.

For these reasons, consideration of environmental impacts is critical for business sustainability and will become more important as society moves towards less pollution and waste over the next decade. The goal of this report is to outline various initiatives that tie together product design and the environment in order to meet more stringent environmental policies and social concerns.

ENVIRONMENTAL INITIATIVES FOR PRODUCT DESIGN

DESIGN FOR ENVIRONMENT (DFE)

Design for Environment (DfE), is a current initiative being advertised to the Canadian automotive parts manufacturing sector by Natural Resources Canada (NRCan)[3]. The definition used by NRCan for DfE is "the systematic integration of environmental considerations into decisions that are made in product and process design"[3]. The information for making such decisions is derived from the various stages of a product's life cycle, which includes the design, production, end use and end-of-life phases.

Because of the drivers listed in the introduction, and subsequent benefits, some companies are starting to implement the DfE approach into their design process. One such example is Magna International Inc., one of the largest automotive suppliers in North America. Since Magna is a major parts supplier for GM, it has a vested interest in maintaining its relationship with the big automaker and in adapting an environmental designs approach. Recently Magna personnel took part in a DfE case study in conjunction with NRCan and other public, private and academic partners. The goal was not only to demonstrate the business benefits of DfE, but also to help construct a framework for implementing DfE in the automotive sector. The information gained will be a valuable tool for Magna in the years to come. This is especially true when considering the more recent GM announcement, which was to meet the goals outlined in the European End-of-Life Vehicles Directive for 2015. This directive states that, by 2015, all vehicles must be 95% recyclable.

DESIGN FOR RECYCLING (DFR)

Various European legislations, including the Take-Back Law and the End-of-Life Vehicles Directive, have developed a more popular, but related, environmental initiative called Design for Recycling (DfR). The European Take-Back Law requires all automobiles to be taken back by their original manufacturer at their end-of-life. The DfR approach encourages consumer-goods manufacturers to design or implement products in such a way that they can be safely and economically recycled when they reach their intended end-of-life[4]. The initiative also states that, when the product is designed, it must be recyclable using existing technologies and practices. DfR is a very important aspect of the sustainable development policies put forth by the consumer goods industry in the EU[5]. Most of the literature pertaining to the DfR comes directly from the EU since it has been at the forefront of worldwide recycling for decades due in part to the scarcity of landfill sites.

Objectives of DfR

The main goal of DfR is to improve a product's recyclability by minimizing the number of materials and components, avoiding the use of toxic materials, making disassembly easier (not only the product but also dissimilar materials), and minimizing the amount of landfill. However, many authors have written that there is no special antidote for achieving these goals other than through creative thinking. On the other hand, it is extremely valuable that the design team does know: (1) the processes they are designing for, and (2) the critical technical and economic factors in each process. It is through these two factors that guidelines can be developed and environmental achievements realized.

To better understand the common processes used in recycling, and their corresponding technical and economic aspects, it is imperative that information pertaining to a product's life cycle, the various avenues of recycling, material compatibility, and disassembly technologies be presented first. Once this material has been reviewed, the focus will shift to outlining DfR guidelines that have been suggested by various industrial organizations.

Life Cycle Analysis

Figure 1 shows a complete life-cycle flowsheet for a typical consumer product. A product's life cycle can be broken down into four distinct stages: design, production, use, and end-of-life. The design phase represents a series of events that translate market or customer needs into concepts, drawings and models, that all come together to generate a product that meets the initial needs[6]. The production phase consists of the physical production of all materials and components, and their assembly, to manufacture the product. The use phase represents the time frame during which a product is operated or consumed. Lastly, the end-of-life phase represents a product that no longer serves its intended function or is no longer used for its intended purpose. At this point, the product can either be stored, dismantled, incinerated, sent to landfill, recycled, partially reused or some combination of the above. The term 'demanufacture' (Fig. 1) is commonly used in the electronics industry to represent a process opposite to manufacturing that is involved in recycling materials and products.

It is imperative that a design team become familiar with the different phases of a product's life cycle so that they will be able to answer key questions relating to its end-of-life phase. Some of these questions are listed in Table 1, for reference only, and will not be discussed in more detail.

Recycling Streams

A product can be recycled using a number of different avenues including: direct recycle or reuse, remanufacture, raw material regeneration (recycling), and incineration for energy. The most preferred option for recycling does not pertain to an individual stream but rather to a reduction in both the amount and the variety of metals in the product. It is through these two concepts that the quantity of waste material and the difficultly of recycling can be lowered. In terms of particular avenues, the hierarchy of recycling options is listed in Fig. 2. Re-use is the next highest priority from an environmental point of view since all of the original resources used to generate the product are saved. This encompasses both raw material and energy. In addition it does not require destructive disassembly, which can be costly depending on the practice required. However material recycling is the most common form and typically requires some type of destructive disassembly. In material recycling, only the material value is captured, while the energy input into the geometric details are lost. Energy recovery encompasses both combustion and pyrolysis, with the former being the more common technique employed. In normal combustion practices, mostly organic materials are used (paper and plastic). Landfilling is not considered a recycling option but is included in Fig. 2 to represent the very last stage in a product's end-of-life phase.

The difference between re-use and recycle is that the former is recovered from the waste stream for use in its original application while the latter is used as a raw material in the manufacture of new products. Therefore remanufactured components would fall under the category of re-use. In addition, materials that are used to produce energy through incineration do not fall under either of these categories, but are classified under energy recovery. In Europe, energy recovery is considered a viable recycling option. It should be noted that these two definitions were taken from the American Automobile Manufacturers Association (AAMA), and they might be different from classification systems used in Europe. The US Environmental Protection Agency (EPA) also indorses these definitions.

In order to determine the correct recycling-avenue for each part in the overall component, numerous institutions have constructed end-of-life flowcharts. One such example is shown in Fig. 3.

Material Selection

Over the last two decades, the amount of materials used in common consumer products has increased significantly, making it very difficult for recyclers. The four main categories of materials typically found in the recycling world are:

- Metals
- Plastics
- Paper
- Glass

Ceramics, which are being used increasingly in the electronics industry, were not included since they are not being actively recycled because of their small size and insignificant value. Depending on the type of recycling industry being discussed, various proportions of each material class can be found. For example, in automotive recycling metals far outweigh any other class of material, while in municipal waste streams paper and glass are more common. For the purpose of this report, only metals, plastics, and glass will be discussed since they are more commonly found in consumer products.

Various compatibility tables exist for outlining what materials in a specific class can be recycled together. The majority of these lists, however, is geared towards plastics. One such example is shown in Appendix B. Thermoplastics – such as low-density polyethylene, polypropylene, polyvinyl chloride, and polyethylene terepthalate – are generally easy to recycle. On the other hand, thermosets (polyesters, epoxides, and phenolics) are harder to recycle because of their high degree of cross-linking, and they need pyrolysis/hydrolysis before recycling in order to reduce their molecular weight.

Compatibility charts for glass are also very common, and a typical example is shown in Table 2. Additives are cited as the main reason for the incompatibility of various sources of glass products. Boron, for example, is used for thermal and electrical resistance while cerium is used to absorb infrared rays.

In comparison, metals are easier to recycle, therefore compatibility charts are less common. However, a variety of guidelines and rules do apply and will be discussed below.

Since coatings are a major source of contamination in recycling, uncoated materials are much easier to recycle than their coated counterparts. It should be noted that coatings not only encompass plated metals but also include various laminates and paints that are typically used for both metals and plastics. Metals with a high alloy content are harder to recycle because of their large residual elemental concentration. These elements represent another source of contamination especially when other low-alloy metals are included in the feed material. Due to advancements in material separation technologies, steel, aluminum, and magnesium can be separated quite easily. However steel contaminated with copper, tin, zinc, lead, or aluminum is more difficult to recycle. Similarly, iron, chromium, zinc, lead, copper, or magnesium contaminants in aluminum also lower its apparent value and recyclability.

Therefore in the material selection process of the design stage, recycling compatibility should be a major consideration. In addition, exotic materials should be avoided, especially ones that pose a risk to humans and the environment. Moreover plastics should be adequately marked so that they can be readily identified during normal dismantling practices. Misidentification of recyclable plastics is the number one reason why plastics have such a low recyclability.

Disassembly Technologies

For re-use and remanufacture, the following processes are required to prepare a component for secondary use:

- non-destructive disassembly,
- cleaning,
- inspection and sorting,
- part upgrading or renewal, and
- re-assembly.

For material recycling, the processing avenues consist of both destructive and non-destructive disassembly, materials separation, sorting, and reprocessing. In the framework of this report, the term ‘sorting’ will refer to the classification and separation of materials with the same matrix (elemental). For example, after complete material separation, aluminum scrap can be further sorted into its different alloy classifications (1XXX, 2XXX, etc).

The main type of destructive disassembly is shredding. The development of shredding technology was one of the leading factors in automotive recycling becoming economical since it could easily fragment the vehicle hulk into very small pieces and allow for easy and consistent separation by various techniques: magnetic separation, air knife classification, density based sink-float plants, eddy current, etc. Other separation processes are being examined, mostly small or pilot scale, to combine materials separation and sorting into one automated process; however low wages in Asia have hindered this development. Such technologies include Fourier Transform-Infrared (FT-IR), FT-NIR (near infrared light), and FT-Raman (YAG laser).

Most non-destructive disassembly systems are manual operations, and their economic viability is dependent on time and labour cost. Activities involving loosening screws and bolts are typically the primary consumer of time and represent a significant portion of the manual disassembly cost. In an example given for the remanufacture of a four-cylinder internal combustion engine, removing common fasteners represented 54% of the entire disassembly process. Therefore, making manual disassembly easier is a definitive way of making recycling more economical since it decreases time and increases the amount of parts for either direct re-use or re-manufacture. This has, in turn, spurred the Design for Disassembly (DfD) initiative, that looks at choosing fasteners to facilitate disassembly and material separation for not only non-destructive but destructive techniques. One of the most common ways to achieve this goal is to reduce the number and types of fasteners used in the assembly of a product. Because some fasteners are easier to remove than others, various tables have been developed to outline the preferred types. One such example, based on of a German fastener rating system, is shown in Appendix B. In addition, all ferrous fasteners should have a coating to protect the underlying material from corrosion. Severely corroded fasteners make manual disassembly much more difficult and costly. On the same note, coatings that are detrimental to the refining process (material compatibility), human welfare, and the environment should be avoided. For instance, cadmium coatings are recognized as a potential health and environmental hazard and should be banned entirely. In cases where they do not reduce the integrity of the product, snap fits should be implemented to reduce the number of fasteners.

There are clear logistical differences in fastener selection between non-destructive and destructive disassembly systems since fasteners in the latter will not be removed but rather combined with the rest of the shredder residue. Thus for destructive disassembly systems, it is important that the fasteners selected be made of the same material as the product itself so that no material separation is required after shredding. If plastic fasteners are not sufficient for a plastic component, ferrous fasteners should be implemented so that standard magnetic separation practices can be used. If adhesives are employed in the assembly of the product, it is essential that they be compatible with the main product material so that the feed material does not become contaminated for secondary material processing.

One of most challenging tasks for many design teams is identification of the type of separation process to best improve the recyclability of their product. The first step in completing this task is to take the proposed design and determine the manual removal rate for each different material class. If the material removal rate (MRR) is high, then a non-destructive disassembly system should be selected. The MRR for plastics has been cited at 5 kg/min in order for manual separation to be economical[9]. Unfortunately, statistics for the other material classes were not found. If the MRR is considered low, then the design should be reconsidered in regards to disassembly. If design improvements can be made to increase the MRR to the level required for manual disassembly, they should seriously considered. However if improvements cannot be made, then a form of destructive disassembly should be implemented.

Economics

In order for a recycling effort to be successful, it must be profitable without government subsidies. For most recycling operations, the majority of the revenue is generated from the parts that are directly reusable. The second and ternary sources of income are from the materials recycling and energy recovery operations. In some industries, materials recycling can be the leading source of revenue if precious metals are incorporated (electronic industry – gold).

The major cost for most operations is the initial investment in all of the recycling equipment required to disassemble the component. Equipment costs are dependent on the type of disassembly required: non-destructive or destructive. Other (variable) costs include labour, transportation, and equipment operating expenditures (service, maintenance, etc). Generally the cost associated with obtaining the component is low, but once again this is dependent on the condition of the part and the value of the materials contained within. Another expense is landfilling, the cost of which is inversely proportional to the number of disassembly steps required for the recycling process. This is because the overall recycling rate typically increases with the number of disassembly steps since the amount of material to be landfilled decreases. However with each new disassembly step, the fixed and variable costs also increase, making it imperative that the recycler perform an adequate analysis first.

For a manual disassembly system recycling old electronic equipment, the amount of material (grams) required to be removed per minute to make the process cost neutral was estimated and is shown in Table 3.

It should be noted that the data in Table 3 were based on European figures in 1995 at a labour cost of US $36/h and therefore does not completely reflect today's recycling system. However, it is believed to provide a reasonable reflection of the economics surrounding a manual disassembly system.

Another cost example is outlined in Appendix Cand looks at the economic viability of recycling an automotive dashboard. According to the source document[8], the amount of time required to completely remove a dashboard from a car is 35 min. In addition another 35 min is allotted for removing the individual components from the dashboard. Using a wage of US $20/h, the total labour cost per dashboard is $23. Appendix C lists all of the different materials contained in an average dashboard (in 1990), the weight of each material and its corresponding percentage of the entire dashboard, as well as the virgin and scrap prices for each material. By quickly analyzing the numbers, it can be seen that only 10 kg of copper (the highest valued material within the dashboard) would need to be recycled per hour for the operation to break given.

Industrial Guidelines for DfR

Guidelines have been created to better enable design teams to achieve their environmental initiatives. The remainder of this report will illustrate four DfR guidelines that have been suggested for industrial applications by various companies, organizations, and institutions.

ARCELOR

Between 1995 and 2000 ARCELOR, a large French steel recycler, conducted an intense research and development program titled "The Cycle of Iron" the objective of which was to determine the sustainability of steel recycling within France. The initiative encompassed all of the major players in steel recycling including producers, consumers, recyclers, and various government bodies and focused on four key areas:

1. availability and accessibility of the resource,
2. reliability of scrap to represent a high-quality secondary raw material and possible measures to improve quality,
3. ability of steelmaking practices, either integrated or mini mill, to employ more scrap, and
4. re-examination of steel specifications in order to remove unnecessary constraints that would deter the use of scrap material.

The second half of the document focused on a simple, but effective, approach to DfR and will be outlined below in four stages. It was suggested that design departments performing a DfR analysis could use this approach and find reasonable success.

Stage 1

The first stage is to identify the lists of materials that are forbidden by government, industry, and consumer and environmental groups. The lists (usually red, yellow, or green) outline materials that present legitimate health and safety concerns either in the workplace, to the consumer, or in the environment. After the lists have been compiled, the focus of the design is to avoid using the restricted materials or quickly phase them out of the current product.

Stage 2

Stage 2 addresses the recycling route, which should be determined in the early stages of the DfR process. The overall goal of this stage is to develop a list of processes that would be required to adequately recycle the product. It is imperative that each process be well investigated to avoid using materials in the operation that would pose a risk to the environment. For example, ARCELOR developed an internal system to assess the recyclability of its own products. Each new grade of steel being produced is melted and subjected to various tests including pyrolysis, emissions, and oxidation, to determine its effect on the environment.

Stage 3

The third stage is an investigation conducted to determine the quality of the recycled product after it has been recovered. If the recycled stream does contain impurities, further investigation is required to determine whether they can be effectively removed in the refining shop. In the case of steel recycling, some elements cannot be removed in either the basic oxygen furnace (BOF) or the electric-arc furnace (EAF) using current refining practices (i.e., copper). This leaves dilution as the only method available to reduce the contaminant's concentration within the steel melt, which is very expensive and time consuming. Similarly, iron and silicon have the same effect on aluminum. Therefore it is imperative that these damaging elements be removed prior to refining through either physical or chemical sorting methods.

If these contaminants cannot be removed from the secondary material, then the industry as a whole needs to work together to solve this material problem. In the case of copper in secondary steel (most often originating from copper wires in various motor cores), the automotive industry could replace all copper wiring with aluminum. Aluminum is readily removed from molten steel by injecting oxygen into the bath. Aluminum has a high affinity for oxygen, causing it to quickly oxidize and settle out of the metal and into the slag. Another solution is to better design motor cores so that they quickly break up during normal shredding operations and release their internal wiring. An R&D initiative in the EU has already designed and marketed such a motor core using powder metallurgy[5]. Once the copper wiring is released from the core, standard magnetic separation units can quickly separate it from the remaining material.

Stage 4

The fourth stage looks at the amount of burnable 'gangue' that is adhered to the metal. In some metal industries, the tolerance for such material is very low (aluminum). The steel industry is slightly more tolerable, however the ability of the EAF to incinerate the organic material is dependent on the power of the furnace being used. In addition, the emissions from this organic material cannot be easily controlled in the smokestack and result in sporadic releases of GHG. Thus, the organic matter should be removed in the material feed preparation system.

Although this is a rough DfR outline, it is considered to be sufficient for a macro-design or top-down approach rather than a micro-design or bottom-up approach. The latter approach is typical of most other eco-design programs.

EU Approach

The EU has developed a simplistic approach to DfR to help companies choose the optimum metal-to-non-metal ratio when designing a product to meet European Directives on recycling. In this approach, a recycling expression was derived that looked at the percentage of metals (M) and non-metals (P) in a typical consumer product. Since metals were considered completely recyclable and non-metals, at the time of publication[5], were being recycled at a 15% efficiency, the following recycling equation was formed:

$$M + 0.15\propto P \qquad \text{Eq 1}$$

where $\propto$ represents the percentage of non-metals being recycled. The EU Directive for 2006 stated that all consumer products must be at least 80% recyclable. The above equation was then re-written to reflect this minimum requirement:

$$M + 0.15\propto P = 0.8 \qquad \text{Eq 2}$$

In addition, the mass balance equation was expressed by:

$$M + P = 1 \qquad \text{Eq 3}$$

Both equations were graphed based on different values for $\propto$, and the results are shown in Fig. 4.

The curves for each alpha represent the minimum amount of metal to be used in a consumer product and still satisfy the 2006 EU recycling regulation. In this example, the metal content ranged between 77-80%, depending on the value for alpha.

Other important conclusions were also drawn from the example given above. For instance, metals were the leading factor in meeting the directive since they were completely recyclable.

Moreover, the amount of non-metals being recycled had very little effect on the metal requirement since their recycling efficiency was so low.

It should be noted that Eq 2 represents a basic DfR approach and does not address the other conditions outlined in the EU regulations (i.e., the amount of energy recovered and landfilling). However material selection between metals and non-metals was deemed the most important condition for recycling and represented the initial basis for implementing the EU Directive.

Because of the significance of the EU Directives in developing and continually evolving the DfR approach, a quick overview of its targets is going to be performed for both automobiles and appliances. The targets for both automobiles and appliances are broken down into three categories – the amount of recycling, energy recovery, and landfilling – and are outlined in Figs. 5 and 6, respectively. In addition to the target values, average results from industrial recycling operations in France (as of 2002) are also listed to help gauge how far the industry is from meeting the first directive in 2006 and the second in 2015.

By examining Fig. 5, it appears that the recycling targets set out in the 2006 directive were already being met in 2002 and directly reflected the amount of metal being used in the automotive industry. The energy recovery constraint was satisfied in one of the industrial averages but was lagging in the other. However it was believed that the target could easily be met by the combustion of ‘burnable’ plastics inside a better energy recovery system. In 2002, the efficiencies associated with energy recovery systems were quite low in France.

The amount of landfill required to recycle a single vehicle in 2002 also varied from source to source, reaching as high as 17.5% in one industrial operation and 12.5% in another. It appears that this difference might be attributed to the operation of an energy-recovery system in one recycling stream compared with the other (burning plastics). This seems reasonable given the fact that no energy-recovery statistics were given for one of the industrial references. Regardless of this issue, in order for landfilling targets to be satisfied in 2006 and 2015, common plastic materials will either need to be replaced or made more recyclable. It is believed that the former is the most logical direction and will be adopted by most European automotive companies.

In the case of appliances, meeting the 2006 directive seemed to be a bigger challenge because of the greater use of non-metals. In addition, appliances appear to be much more complex in regards to recycling, energy recovery, and landfilling because of the variance in the industrial results shown for each category (Fig. 6). If the appliance averages are compared, the recycling targets appear to be well in hand, however the amount of landfilling appeared to be high in the first source, which was most likely due to the lack of an energy-recovery system since no energy statistics were outlined. Therefore all ‘burnable’ non-metals (mostly plastics) were most likely landfilled directly. However, when the appliances are broken down into their individual classes, it appears that fridges and dishwashers were well under the recycling target in 2002 while stoves were already meeting the target values set forth for both recycling and landfilling. One way to increase the amount of recycling from a washing machine is to substitute the concrete counterweight with a steel version. The concrete typically ends up in landfill, while the steel can be easily recycled.

German Engineering Standard VDI 2243

This particular standard was developed by Germany's leading engineering society, VDI, to help engineers design products for easier recycling by outlining important technological issues. A general outline of their DfR approach is shown in Appendix D. The outline can be broken down into three separate phases: assessment and planning, improvement, and implementation and documentation.

US Vehicle Recycling Partnership (VRP)

In order to help companies boost their recycling rates for current and future products, the U.S. Vehicle Recycling Partnership has recommended a recyclability-assessment method based on a specific rating system. A four-step approach is used to outline whether it is technologically and economically viable to recycle a particular product in the current recycling infrastructure. The four steps of the assessment are:

1. identify the components, materials, and fastening mechanism in the product;
2. rate the components according to a pre-fabricated rating system;
3. determine the recyclability percentage by weight; and
4. identify areas for improvement.

Step 1

The main objective of the first step is to list of all materials used within each component. After the list is constructed, it should be reviewed to ensure that none of the materials raise concerns from a health and safety point of view for either humans or the environment. In addition, any surface pre-treatments and bonding agents must be identified since they can represent significant sources of contamination. For instance, in recycling plastics, a material contamination of only 1 wt % can ruin an entire charge of high-grade material.

This step is critical since the different material types generally dictate the recyclability of a component. The next biggest factor is the determination of the fastening mechanisms used to piece all of the different materials together; this is because these mechanisms identify the separation mechanisms required for either re-use or material recycling. For instance, permanent joining mechanisms, such as welding, almost always require the use of a mechanical separation technique, which are typically destructive. Non-permanent connections, like bolts and screws, can be removed manually, but this technique is usually uneconomical unless the fastener material(s) are sources of contamination. Therefore the fastener material should not be overlooked in the initial material study.

Step 2

In step two, each component is rated on two different classification systems to determine its overall recyclability. These classification systems are referred to as the recyclability rating (R.R.) and the separation rating (S.R.). The scales of each rating system are such that the lower the number the better the rating, with 1 being the best. Ratings 1 through 3, for both classifications, are perceived as acceptable for the European market and should be used as a recycling benchmark in North America. Ratings 4 through 6 are considered poor and do not represent a recyclable component. It should be noted that the U.S. Federal Trade Commission (FTC) rules are more stringent and require a minimum rating of 2 to be considered recyclable. Table 4 provides an overview of the conditions that are required to be met for each recyclability rating. The conditions and definitions of the material separation system are shown in Table 5.

For illustration purposes only, guidelines or rules of thumb for both rating systems are shown in Appendix E and Appendix F.

Step 3

The calculation used to quantitatively assess a component's recyclability (by weight percent) is as follows:

$$\text{\% Recyclability} = \frac{\text{Total weight of components with R.R. and S.R. between 1 - 3}}{\text{Total weight of assembly}}$$

This number represents the total weight of the component that can be recycled and is essential for performing an economic analysis since it is the weight of each material that dictates the revenue generated.

Step 4

Any components with an R.R and/or an S.R. of 4 or greater represent areas for improvement and should be immediately addressed. Because revenues are tied into material weight, and subsequently the overall weight of the component, it is practical that heavy products be reviewed first for improvements.

Appendix G illustrates a typical DfR assessment using the VHP approach outlined above. Please note that this assessment is only a reference and will not be discussed in further detail.

CONCLUSION

Over the next decade, DfR will play an increasing role in the design of products and processes due to increased social and political pressure on manufacturers to reduce their adverse effects on the environment. In order to increase the recyclability of a product, and decrease the amount of landfilling, the following objectives need to be met:

- reduce the variety of materials and components,
- avoid use of regulated and restricted materials, and
- make disassembly of dissimilar materials easier.

Reducing the complexity of a product by decreasing the number of parts and different materials is one of the biggest factors in obtaining a more recyclable product. Meeting these conditions would help reduce the amount of labour required during non-destructive disassembly and maximize the potential of component re-use. Moreover, material separation and sorting practices after destructive disassembly (i.e. shredder) would be simpler, and sources of contamination would be reduced. Material contamination still represents the biggest obstacle for recycling since only a minute level is required to make the process uneconomical.

No materials that present an associated environmental, health, or occupational safety hazard should be considered during the material selection phase of a product's design. Moreover, proper material selection for coatings and fastening mechanisms must also be conducted. For example, lead-based solders should be avoided since lead can accumulate in the secondary feed stream and cause enormous problems for the recycler.

In order to facilitate disassembly for the recycler, it is important for the product to be designed for disassembly. Snap or pop fit, bolts, or screws should be used whenever possible, and permanent assembly techniques should be avoided (welds, adhesive, threaded connections). The designers should determine the feasibility of part reuse and materials recovery, and manufacture an optimum disassembly path by considering the relationship between material recovery and cost.

By taking these objectives into consideration when designing a product, a higher percentage of its components and materials should be recyclable through direct re-use and/or materials and energy recycling. This will in turn reduce waste and demand for landfilling, which is essential for improving the environment.

One of the most significant factors forcing implementation of the DfR approach in design of consumer goods is the EU Directive for automotive recycling. This has caused automakers to replace non-recyclable materials (plastics) with more recyclable options (metals) in an effort to meet the first mandate in 2006 and the second in 2015. It is believed that similar directives will be implemented in North America over the next decade causing some companies to take action. For example, the Big Three car companies have formed the Vehicle Recycling Partnership (VHP) and the Vehicle Recycling and Dismantling Center to look at recycling issues within North America. Moreover, the VHP has proposed a recyclability assessment method to help automotive part suppliers improve their products' recyclability.

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Table 1 – Key questions in identifying an end-of-life system[8].

Category	Questions
Profile the product's current end-of-life system	• Who owns the product? • What kind of ownership is involved? • What is the price? • How big is the product? • What is the average life of the product? • What is the weight of the product?
Analyze key reasons why users dispose of the product	• Is the product disposed of because of technical failure? • Is the product sensitive to trends? • Are there new products on the market that offer more features?
Identify all legislations and regulations that affect the end-of-life system	• To what extent is the manufacturer responsible for the end-of-life phase? • Does a take-back obligation already exist for discarded products? • How can the costs of returning and processing the product be financed? • What rules and prices apply with regard to product reuse, material recycling, incineration and dumping of residual wastes?
Contact the suppliers	• Due to specialized expertise, suppliers can usually achieve sub-assembly reuse, recycling more efficiently than the OEM
Determine how the product will be collected	• Consumer return system via recycling center • Pick-up from last user • Return system via retailers

Table 2 – Material compatibility chart for glass[9].

	Bottle glass	Window glass	Drinking glass	TV (screen)	TV (cone)	TV (neck)	LCD screen
Bottle glass	+	–	–	–	–	–	–
Window glass	+	+	+	–	–	–	–
Drinking glass	+	0	+	–	–	–	–
TV (screen)	0	0	–	+	0	-	–
TV (cone)	–	–	–	–	+	+	–
TV (neck)	–	–	–	–	–	+	–
LCD screen	0	0	–	0	–	–	+

Table 3 – Material weight requirement for cost-neutral recycling[9].

Material	Grams per minute
Precious metals	
Gold	0.05
Palladium	0.14
Silver	5.1
Metals	
Copper	300
Aluminum	700
Iron	50 000
Plastics	
PEE	250
PC, PM350	
ABS	800
PS	1000
PVC	4000
Glass	6000

Table 4 – Rating system for recyclability[9].

Rating	Condition	Definition
1	Part is remanufacturable	Component completely remanufacturable
2	Recyclable, infrastructure and technology are clearly defined	Component completely recyclable and infrastructure clearly outlined and existing
3	Technically feasible, infrastructure not available	Collection avenues not defined or lacking structure, however technology for recycling the materials exist
4	Technically feasible, additional material development required	Recycling technology has not been commercialized
5	Non recyclable organic material for energy recovery	Economical technology for energy recovery established
6	Inorganic material with no known technology	Technology for recycling unknown

Table 5 – Rating system for material separation[9].

Rating	Condition	Definition
1	Disassembled easily, manually	Time to disassemble is less than a minute
2	Disassembled with effort, manually	Time to disassemble is one to three minutes Component may contain a compatible coating
3	Disassembled with effort, mechanical separation or shredding required and technology developed	Component may contain a non-compatible coating(s) and adhesive(s)
4	Disassembled with effort, mechanical separation or shredding required but technology not developed	Component may contain a non-compatible coating(s) and adhesive(s) Technology realized but under development
5	Cannot be disassembled	Technology for separation unknown

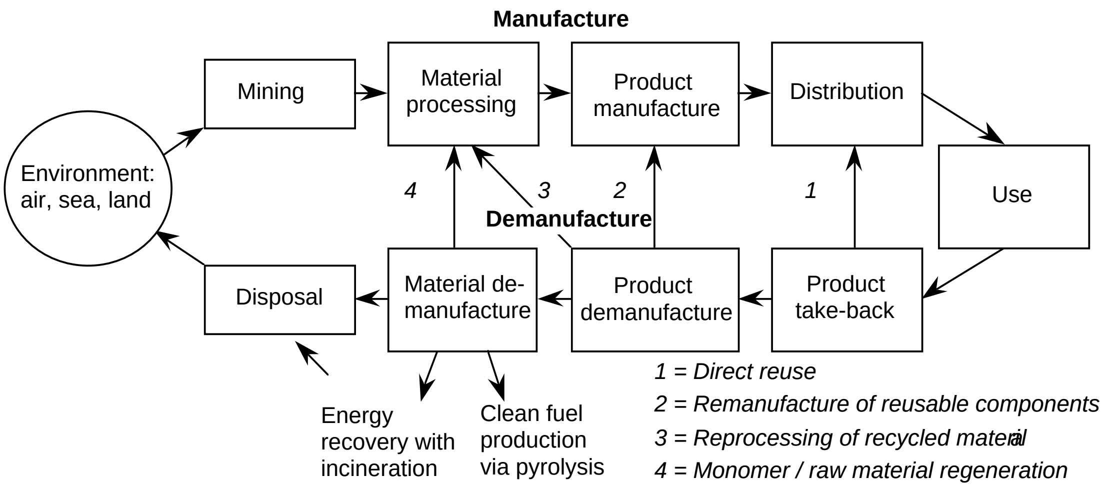


Fig. 1 – A product's life cycle flowsheet[7].

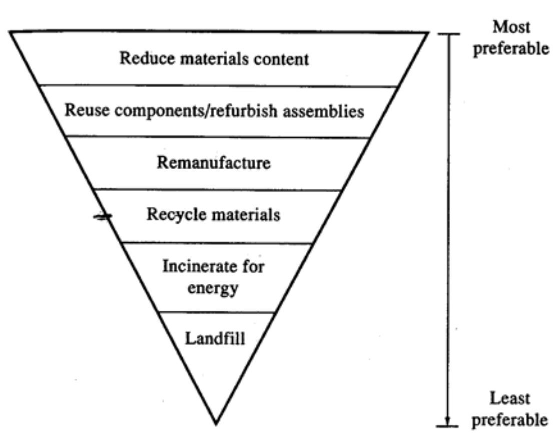


Fig. 2 – Most to least preferable recycling options[7].

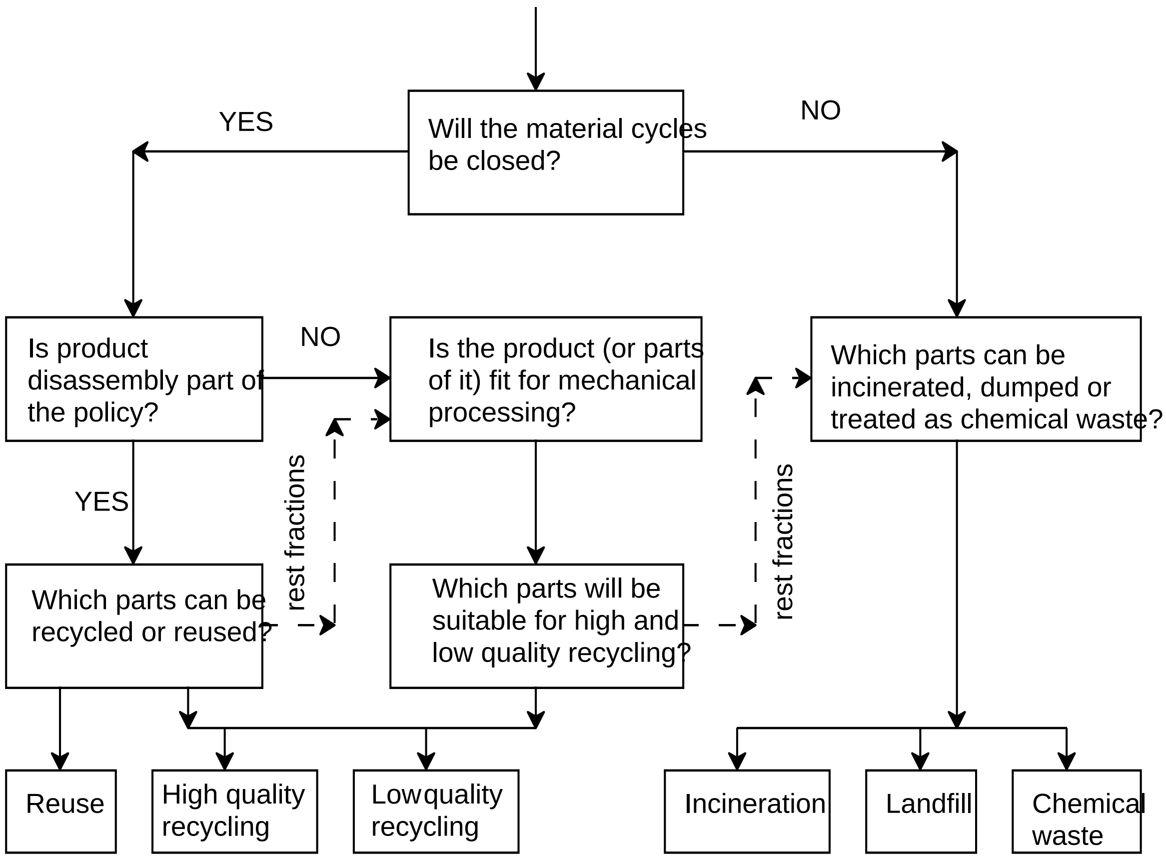


Fig. 3 – Example of an end-of-life destination flowchart[9].

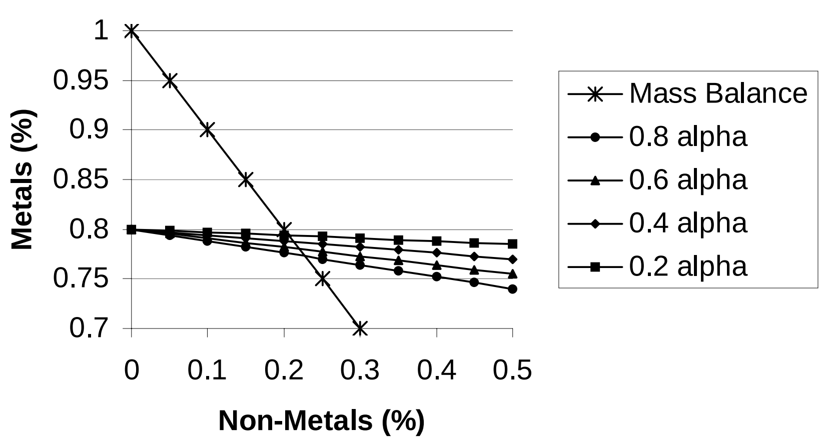


Fig. 4 – Simplified DfR approach put forth by the EU[5].

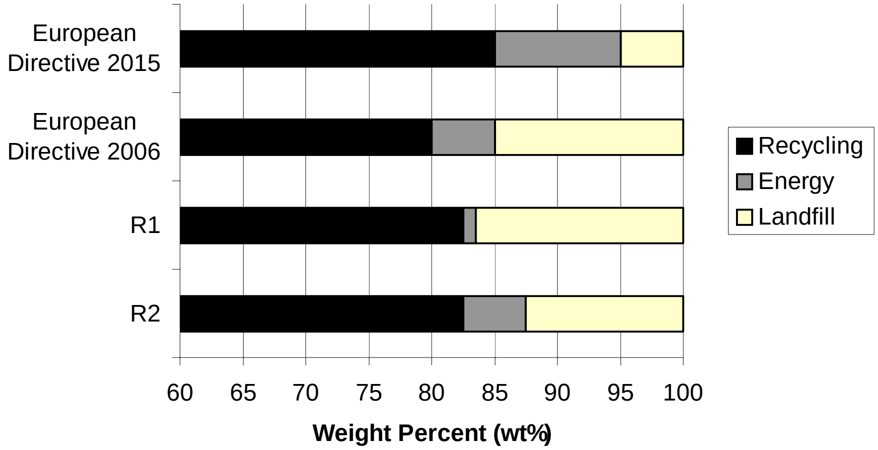


Fig. 5 – Automotive targets for both European directives and corresponding industrial statistics (R1 and R2) in France as of 2002[5].

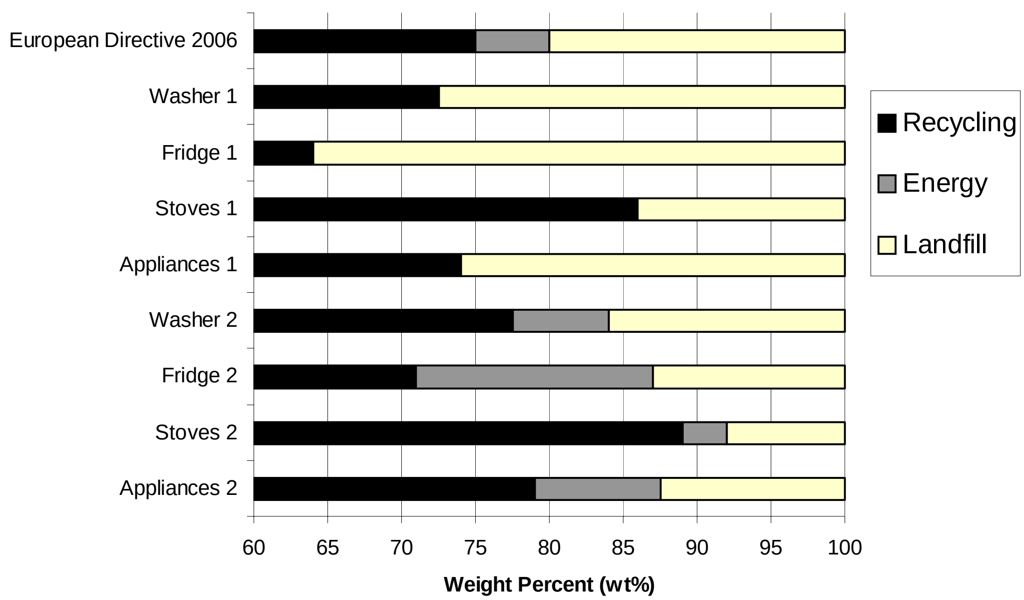


Fig. 6 – Appliance target values for the 2006 EU directive and corresponding industrial recycling statistics from France (2002)[5].

APPENDIX A – MATERIAL COMPATIBILITY CHART FOR PLASTICS[9]

		Additive											
	Important plastics	PE	PVC	PS	PC	PP	PA	POM	SAN	ABS	PBTP	PETP	PMMA
Matrix material	PE	●	○	○	○	●	○	○	○	○	○	○	○
	PVC	○	●	○	○	○	○	○	●	◐	○	○	●
	PS	○	○	●	○	○	○	○	○	○	○	○	○
	PC	○	◔	○	●	○	○	○	●	●	●	●	●
	PP	◔	○	○	○	●	○	○	○	○	○	○	○
	PA	○	○	◔	○	○	●	○	○	○	◔	◔	○
	POM	○	○	○	○	○	○	●	○	○	◔	○	○
	SAN	○	●	○	●	○	○	○	●	●	○	○	●
	ABS	○	◐	○	●	○	○	◔	○	●	◔	◔	●
	PBTP	○	○	○	●	○	◔	○	○	◔	●	○	○
	PETP	○	○	◔	●	○	◔	○	○	◔	○	●	○
	PMMA	○	●	◔	●	○	○	◔	●	●	○	○	●

● compatible
◐ compatible with limitations
◔ compatible only in small amounts
○ not compatible

APPENDIX B – FASTENER RATING SYSTEM FOR BOTH PRODUCT AND MATERIAL RECYCLABILITY[9]

characteristics of connection \ principle of connection		Material Connection		Frictional Connection					Positive Connection					
		plastic/metal adhesive bonding	welding	magnetic connection	Velcro fastener	bolt/nut	plastic bolt/nut	spring connection	snap joint	bent-lever connection	1/4-turn fastener	press-turn fastener	press-press fastener	band with lock
Carrying Capacity	Static Strength	◐	●	◐	○	●	◐	◐	●	●	●	◐	◐	●
	Fatigue Strength	◐	●	◐	○	●	◐	○	◐	◐	◐	◐	○	◐
Joining Behaviour	Joining Expenditure	◐	◐	●	●	◐	◐	●	●	●	●	●	●	●
	Guidance Expenditure	○	○	◐	●	◐	◐	●	●	◐	●	●	●	◐
Detaching Behaviour	Detaching Expenditure	○	○	●	●	◐	◐	●	○	●	●	●	●	◐
	Destructive Detaching Expenditure	◐	◐			◐	●		●	◐	◐	◐	◐	●
Recyclability	Product Recycling	○	○	◐	◐	◐	●	●	○	●	●	●	●	●
	Material Recycling	◐	●	◐	◐	◐	●	●	●	●	●	◐	◐	●

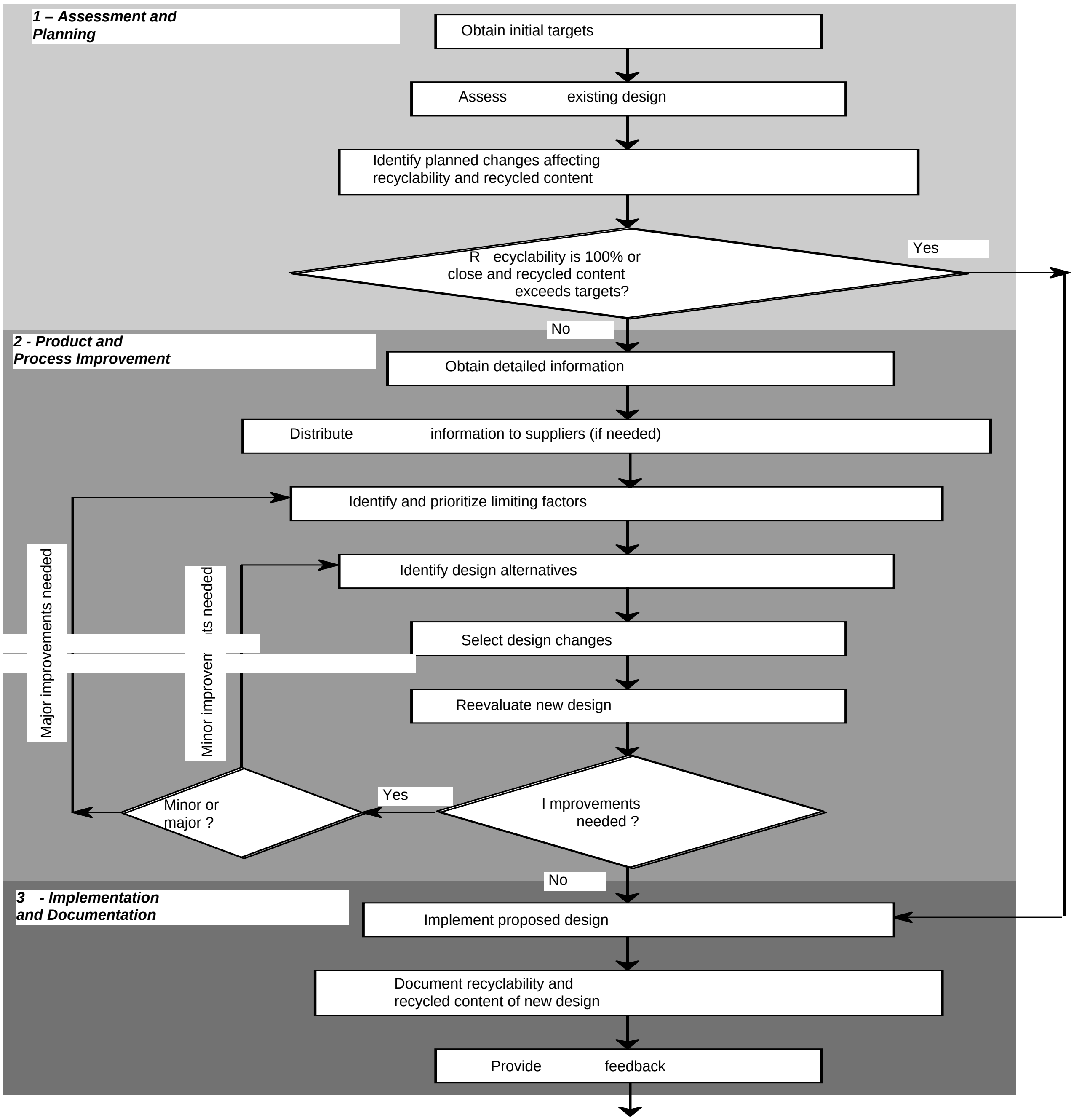
● good ◐ average ○ bad

APPENDIX C – COST ANALYSIS FOR RECYCLING AN AUTOMOTIVE DASHBOARD[8]

Material	Mass		Virgin price	Scrap price
	kg	%	$/kg	$/kg
Steel/Iron	1004	72.38		0.12
Aluminum	71	5.12		1.32
Zinc	9	0.65		1.07
Copper	23	1.66		2.20
Lead	10	0.72		0.25
Polyurethane foam	12	0.87	2.20	0.00
Polypropylene	15	1.08	1.10	0.11
Poly Vinyl Chloride	11	0.79	1.00	0.22
ABS	13	0.94	2.50	0.73
Nylon	10	0.72	3.00	0.00
Polycarbonate	9	0.65	3.30	0.66
Polyurethane	10	0.72	3.50	0.00
Polyethylene	5	0.36	0.90	0.40
Polyester	20	1.44	3.30	0.00
Rubber	61	4.40	2.45	0.05
Other polymers	5	0.36	2.30	0.06
Gasoline	15	1.08		0.30
Oil	5	0.36		0.05
Antifreeze	5	0.36		0.06
Other hazardous fluids	5	0.36		0.00
Glass	39	2.81		0.00
Plastic reinforce fibers	5	0.36		0.00
Plastic composite fillers	5	0.36		0.00
Miscellaneous	28	2.02		0.00
TOTAL	1395	100		

APPENDIX D – DFR GUIDELINE CREATED BY VDI IN GERMANY[8]

Recyclability and Recycled Content Assessment and Improvement Tasks



APPENDIX E – RULES OF THUMB FOR RECYCLABILITY RATINGS[8]

	Component/Assembly material	R.R.	Reason
1	Single metal	2	Technology and recycling infrastructure in place.
2	Single thermo-plastic	3	Technology available, but no infrastructure in place.
3	Single thermoset	4,5	Some technology under development. Incineration may be possible.
4	Multiple metals	2	Technology and recycling infrastructure in place.
5	Single or multiple metals with single thermoplastic	3,4	Shredding and magnetic separation allow for separation of metals, depending on number and types. Resulting residue consists of a single plastic which may be recyclable.
6	Multiple thermo-plastics: All compatible	3,4	Technology is available or under development to recycle this plastic mix, but no infrastructure exist.
7	Multiple thermo-plastics: Incompatible	4,5,6	At best, technology is under development to recycle/separate this mixture. Incineration may be possible, dependent on composition.
8	Multiple thermosets	4,5,6	At best, some technology is under development to recycle/separate part of this mixture. Incineration may be possible, dependent on composition.

APPENDIX F – RULES OF THUMB FOR SEPARABILITY RATINGS[8]

	Situation	S.R.	Reason
1	Fasteners are made of sane, material as part being joined.	1	No disassembly required. All can be recycled as a single part. Preferred situation.
2	Fasteners are made of material compatible with material of parts being joined.	1	No disassembly required. All can be recycled as a single part.
3	Fasteners are incompatible with parts being joined, but easily removable.	1,2	Fasteners can be removed manually. Part material can be separated manually.
4	Fasteners are incompatible with parts being joined, but removable by force (e.g., rivets or heatstakes)	3,4,5	Fasteners can be removed manually. Part material can be separated manually or mechanically if material properties allow.
5.	Fasteners are made of ferrous material and easily removable and parts being joined are made of compatible or same plastic.	1,2,3	Fasteners can be removed manually or by shredding and magnetic separation. Choice depends on time required. Plastic parts are recycled as a mix.
6	Fasteners are non removable/permanent/molded in, but made of ferrous material and parts being joined are made of compatible or same plastic.	3	Fasteners can be removed by shredding and magnetic separation. Plastic parts are recycled as a mix.
7	Fasteners are non removable/permanent/molded in, but made of ferrous material and parts being joined are made of incompatible plastics.	3,4,5	Fasteners can be removed by shredding and magnetic separation. Plastics may be separated through density separation, if number and densities allow.
8	Fasteners and part materials are incompatible and fasteners are absolutely non-removable (e.g., adhesives)	4,5	No separation possible and fastener will cause part material contamination if shredded. In limited cases, (chemical) separation technologies are under development.
9	Part materials are same or compatible, but incompatible with fastener. However, fastener mass is so small that realistically no contamination will occur.	1	All can be recycled as a single part. *Advice from Materials Engineering should be sought, because 1% contamination is already unacceptable in some cases.*

APPENDIX G – EXAMPLE OF A VRP DFR ASSESSMENT[8]

Disassembly activity				Disassemblability					Material recyclability				
No.	Name	Quantity	Type CE/SP/SA	Access	Tool	Force	Time [sec.]	Rating [1-5]	Material	Mass	Rating [1-4]	Rating (1-6)	Marked [y/n]
1	Disconnect mic. from base	1	CE	4	–	4	1	1	–	0	–	–	N
Microphone Disassembly													
2	Remove screws #1 phillips	2	CE	3	#1 PS	4	24	1	Stainless Steel	0.000600	4	2	N
3	From No. 2 Washer	2	SP	4	–	4	1	1	Plastic PP	0.000010	2	3	N
4	From No. 2 Washer	2	SP	4	–	4	1	1	Plastic PP	0.000010	2	3	N
5	Remove keypad subassembly	1	SUB	4	Pliers	2	5	1	Mix	0.000000	1	4	N
6	From No. 5 Gasket	1	SP	4	–	4	1.5	1	Rubber	0.001000	3	2	N
7	From No. 5 Break H-S Tabs	8	CE	1	Knife	1	210	3	–	0.000000	–	–	N
8	From No. 5 Keypad PCB/LCD	1	SUB	4	Pry	4	2	1	Mix	0.000000	1	4	Y
9	From No. 8 Undo metal tabs	6	CE	3	Pliers	3	25	1	–	0.000000	–	–	N
10	From No. 8 Remove. Disp. Sub.	1	SUB	3	–	4	1	1	Mix	0.000000	1	4	Y
11	From No. 10 LCD Cover	1	SP	4	–	4	1	1	Plastic HDPE	0.000750	2	3	Y
12	From No. 10 LCD	1	SP	4	–	4	1	1	Mix	0.002500	1	4	Y
13	From No. 10 Conductor	2	SP	4	–	4	1	1	Mix	0.000030	1	4	Y
14	From No. 10 LCD Base	1	SP	4	–	4	1	1	Aluminum	0.001200	4	2	Y
15	From No. 8 PCB	1	SP	4	–	4	1	1	Mix Cu, Au	0.010400	1	4	Y
16	From No. 5 Keypad	1	SP	4	–	4	2	1	Rubber	0.006100	3	2	Y
17	From No. 5 LCD Prot. Scrn.	1	SP	1	Pry out	1	5	1	Plastic HDPE	0.001000	2	3	N
18	From No. 5 Foam	1	SP	2	Knife	4	1	1	Foam	0.000000	1	4	N
19	From No. 5 Inserts	2	SP	1	Saw	1	30	1	Brass	0.001000	4	2	N
20	From No. 5 Keypad base	1	SP	4	–	4	1	1	Plastic ABS	0.015000	3	2	Y

Disassembly activity				Disassemblability					Material recyclability				
No.	Name	Quantity	Type CE/SP/SA	Access	Tool	Force	Time [sec.]	Rating [1-5]	Material	Mass	Rating [1-4]	Rating (1-6)	Marked [y/n]
21	12-pin connector housing	1	CE	2	Pin	4	50	1	Plastic HDPE	0.000800	2	3	Y
22	Microphone subassembly	1	SUB	3	Pliers	3	7.5	1	Mix	0.000000	1	4	Y
23	From 22 Mic. & wires	1	SP	2	–	3	7	1	Mix Cu, Al	0.000940	1	4	Y
24	From 22 Microphone boot	1	SP	4	–	4	1	1	Rubber	0.001250	3	2	N
25	PTT Contact & wires	1	SUB	1	Pliers	3	5	1	Mix Cu, Au	0.001500	1	4	Y
26	Screw - mic. cord/bracket	1	CE	4	#1 PS	3	10	1	Steel	0.000200	4	2	N
27	Mic. cord bracket	1	SP	3	Pliers	2	8	1	Stainless Steel	0.000600	4	2	Y
28	Microphone cord	1	SUB	2	–	2	25	1	Mix Cu, AU, Pl	0.089300	1	4	Y
29	Mic. cord boot	1	SP	4	–	2	5	1	Rubber	0.001300	3	2	N
30	Spacer	2	SP	4	–	3	3	1	Plastic PP	0.000010	2	3	N
31	Screw - mic./PTT lever mount	1	CE	4	#1 PS	4	10	1	Steel	0.000200	4	2	N
32	Microphone/PTT mount bracket	1	SP	3	Pliers	2	4	1	Plastic ABS	0.005000	1	4	Y
33	Rubber pad	1	SP	3	–	3	2	1	Rubber	0.000900	3	2	N
34	Motorola label	1	SP	2	–	3	5	1	PLastic HDPE	0.000100	2	3	N
35	PTT lever	1	SP	1	Pliers	2	3	1	Plastic ABS	0.000800	2	3	Y
36	PTT bezel	1	SP	2	Pliers	2	3	1	Plastic ABS	0.000500	2	3	Y
37	PTT actuator	1	SP	2	–	4	1	1	Rubber	0.001500	3	2	Y
38	Microphone Hanger	1	SP	4	Drill	1	60	2	Stainless Steel	0.030223	4	2	N
39	Microphone base	1	SP	4	–	4	1	1	Plastic ABS	0.046777	2	3	Y