Design for Disassembly Guidelines

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Introduction

Changing fashion trends and rapidly advancing technology has led to the shortening of life-spans for many of today's products. Cellular (mobile) telephones, cars and personal computers are just some of the products which are constantly re-engineered, re-styled and re-marketed to meet our growing demands for better products. These demands, however, are placing a heavy burden on our natural and physical resources, particularly during manufacture and when the products reach their end-of-life. It is becoming clear that we may not be able to sustain such a fast rate of product-life turnover without considering both the environmental and economic impacts this has on the planet.

Designers are becoming steadily aware of the problem, and are employing techniques that allow them to design with greater responsibility - *Design for Disassembly is* one such technique. It involves designing a product to be disassembled for easier maintenance, repair, recovery and reuse of components/materials. As part of Design for the Environment (DfE) and sustainable product design, Design for Disassembly is becoming increasingly recognised as an effective tool by designers, manufacturers and legislative boards alike.

Why Design for Disassembly?

The reasons for implementing DfD techniques are numerous. Impending WEEE and RoHS legislations have pressurised manufacturers into adopting sustainable product design principles, but designing for disassembly isn't just about meeting legal requirements. Reducing waste in the manufacturing and recovery processes using DfD techniques can significantly reduce production costs and allow for greater technical efficiency. Modular design principles within DfD techniques allow for greater flexibility during product development, shorter development timescales and reduced development costs. Implementing DfD into a design specification allows the product and its components to be better suited for re-use or recycling when it has reached its end of life, thus reducing the scale of resources required to create new products.

Design for Disassembly Principles

When designing products with disassembly in mind, there are three important factors which must be considered by the designer:

- The selection and use of materials
- The design of components and product architecture
- The selection and use of fasteners

In addition to this, the choice of recycling/recovery methods used at the product's end of life can partly determine the recyclability of the product. The resources used in packaging the product can sometimes be factored in.

Material Selection

Studies into vehicle recyclability at the Georgia Institute of Technology, USA suggest that the limiting factor in the economic recycling of complex assemblies found in vehicles (e.g. instrument panels, headlight clusters) is the separation into pure material streams – either manually or mechanically. For manual separation to be carried out, there must be a significant value retained in the recycled product in order for the separation to be economically feasible. This scenario is applicable to most other products constructed from sub-assemblies consisting of a variety of materials.

Different guidelines apply, depending on whether manual or mechanical separation is carried out. As a general rule, however, products with a low Material Removal Rate (MRR) – less than 2.26kg/minute for plastics – benefit from mechanical disassembly, whereas it is more economical to manually disassemble products with a high MMR (approx 4.5kg/minute).
The amount of material (grams) that has to be removed per minute for recycling to be cost-neutral for manual disassembly *(Based on West-European hourly rates and material prices, September 1995)*:

Precious Metals		Metals		Plastics		Glass	
Gold	0.05	Copper	300	PEE	250	Glass	6000
Palladium	0.14	Aluminium	700	PC, PM	350		
Silver	5.10	Iron	50,000	ABS	800		
				PS	1000		
				PVC	4000		

Source: Philips Centre for Manufacturing Technology

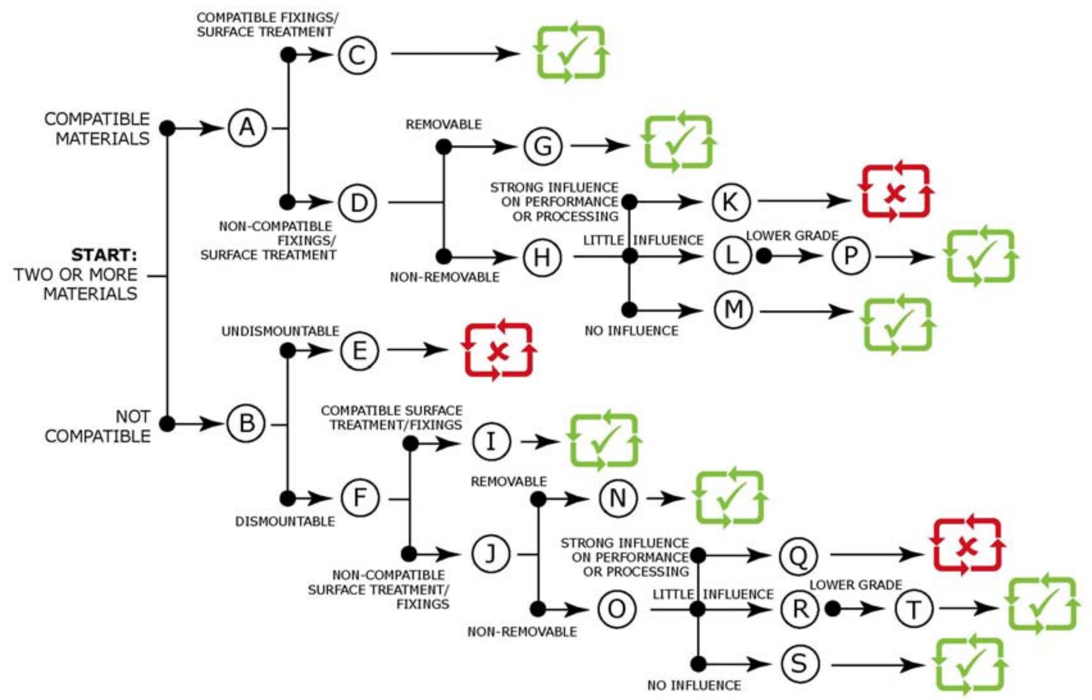

FIGURE 1: RECYCLING OF TWO OR MORE MATERIALS

Reduced separation times for disassembly can be achieved through the careful selection of materials. Indeed some parts may not require disassembly at all if they are made from the same or similar materials. Figure 1 (above) demonstrates all the possible combinations of material for an assembly, and how their properties affect the assembly's recyclability. The table below itemises the number of steps for each combination shown in figure 1. It can be seen that having materials which are compatible with compatible fixings/attachments greatly increases the product's recyclability, while incompatible materials, non-dismountable surface attachments and factors reducing recycling performance increase the steps required for recycling, making it both costly and resource-intensive. In some cases it is just not economically feasible to carry out recycling as the resources required to carry this out far exceed the actual material value of the product.

2 Steps to Recyclability	3 Steps to Recyclability	4 Steps to Recyclability	5 Steps to Recyclability	6 Steps to Recyclability	Not Recyclable
A-C	A-D-G B-F-I	A-D-H-M B-F-J-N	A-D-H-L-P	B-F-J-O-R-T	A-D-H-K B-E B-F-J-O-Q

In an ideal situation, the assembly would be constructed from a single material, although this is rarely case. The shortest “path” towards material recycling is the next best target, and this will largely depend on the material compatibility.

The chemical structures of the materials need to be similar in order to be broken down into their raw form together. The table below outlines the compatibility of plastics:

		Additive											
Matrix Material	**Important Plastics**	**PE**	**PVC**	**PS**	**PC**	**PP**	**PA**	**POM**	**SAN**	**ABS**	**PBTP**	**PETP**	**PMMA**
	PE	1	4	4	4	1	4	4	4	4	4	4	4
	PVC	4	1	4	4	4	4	4	1	2	4	4	1
	PS	4	4	1	4	4	4	4	4	4	4	4	4
	PC	4	3	4	1	4	4	4	1	1	1	1	1
	PP	3	4	4	4	1	4	4	4	4	4	4	4
	PA	4	4	3	4	4	1	4	4	4	3	3	4
	POM	4	4	4	4	4	4	1	4	4	3	4	4
	SAN	4	1	4	1	4	4	4	1	1	4	4	1
	ABS	4	2	4	1	4	4	3	4	1	3	3	1
	PBTP	4	4	4	1	4	3	4	4	3	1	4	4
	PETP	4	4	3	1	4	3	4	4	3	4	1	4
	PMMA	4	1	3	1	4	4	3	1	1	4	4	1

Source: VDI 2243, Georgia Institute of Technology, USA

1 = Compatible
2 = Compatible with limitations
3 = Compatible only in small amounts
4 = Not compatible

Metals are generally easier to recycle, but the following guidelines still apply:

- Unplated metals are more recyclable than plated ones.
- Low alloy metals are more recyclable than high alloy ones.
- Most cast irons are easily recycled.
- Aluminium alloys, steel, and magnesium alloys are readily separated and recycled from automotive shredder output.
- Contamination of iron or steel with copper, tin, zinc, lead, or aluminium reduces recyclability.
- Contamination of aluminium with iron, steel, chromium, zinc, lead, copper or magnesium reduces recyclability.
- Contamination of zinc with iron, steel, lead, tin, or cadmium reduces recyclability.

Source: Georgia Institute of Technology, USA

The selection of materials should in no way compromise the structural requirements of the design. If the properties of a specific material meet the requirements for the design better than others, then it would be an obvious choice (not taking cost into account). However, analogous reasoning should allow the designer to find a material that is widely used in a different context (and is therefore relatively easy to store, recycle and transport) and apply it to the design problem in question.

Regulated/restricted materials often have legislation stating that they MUST be recycled, or at least separated/removed from host assemblies before disposal. It is far easier and more economical to avoid these materials where possible, especially those which pose a safety or environmental risk.

Materials should be marked according to standards (e.g. ISO 1043) for identification purposes. Markings which are moulded into the part are preferable because no additional manufacturing processes are required, although they should not create a stress concentration on the part.

If more than one material is used within an assembly, they should be made from a similar material or at least be easily separable so that they can be recycled individually. Laminates are usually difficult to separate and should ideally be made from recycling-compatible materials.

The use of materials with different properties can be beneficial during the separation/sorting process; the use of magnetic and non-magnetic materials within an assembly, for example, takes advantage of large-scale robotic disassembly machinery. Separation by density is common for plastics – it is recommended that a 0.03 specific gravity difference between polymers is maintained. It is down to the designer’s ingenuity to select appropriate materials for this.

Component Design & Product Architecture

Design for Disassembly through component design and product architecture shares many of the principles used in design for assembly. Designers should:

- Minimise the number of components used in an assembly, either by integrating parts or through system re-design
- Minimise the number of material types used in an assembly
- Separate working components into modular sub-assemblies
- Construct sub-assemblies in planes which do not affect the function of the components
- Avoid using laminates which require separation prior to re-use
- Avoid painting parts as only a small percentage of paint can contaminate and prevent an entire batch of plastic from being recycled.

Use of Fasteners

Fasteners play an integral part in the joining of components and subassemblies.
Designers should:

- Minimise the number of fasteners used within an assembly.
- Minimise the types of fastener used within an assembly.
- Standardise the fasteners used.
- **Not** compromise the structural qualities of the assembly by using too few or inadequate fasteners.
- Use snap-fits where possible to eliminate the need for a fastener
- Consider work-hardening, fracture, fatigue failure and general wear when designing snap-fits.
- Consider the use of destructive fasteners or those incorporating ADSM technology.

If metallic fasteners are used, then ferrous types are preferable (for magnetic separation). However, if the fastener is to be in contact with water and humid conditions, this may be to prevent corrosion. Anodizing is a possible option *(N.B. Cadmium coatings should be avoided, given the potential health and safety risks they pose).*

Access to the fasteners is also important. Holes which are complete (i.e. follow through the entire section of the component) allow for the fastener (e.g. snap-fastener) to be tapped out as opposed to being pulled out.

Consider the table below *(courtesy of GA.Tech)*:

		Material Connection		Fictional Connection				Positive Connection				
		Adhesive Bonding	Welding	Magnetic	Velcro	Nut & Bolt (metal)	Spring Connection	Snap	Bent Lever	¼ turn	Press-turn	Press-press
Carrying Capacity	Static Strength	2	1	2	3	1	2	1	1	1	2	2
	Fatigue Strength	2	1	2	3	1	3	2	2	2	2	3
Joining Behaviour	Joining Expenditure	2	2	1	1	2	1	1	1	1	1	1
	Guidance Expenditure	3	3	2	1	2	1	1	2	1	1	1
Detaching Behaviour	Detaching Expenditure	3	3	1	1	2	1	3	1	1	1	1
	Destructive Detaching Expenditure	2	2	N/A	N/A	2	N/A	1	2	2	2	2
Recyclability	Product Recycling	3	3	2	2	2	1	3	1	1	1	1
	Material Recycling	2	1	2	2	2	1	1	1	1	2	2

1 = Good   2 = Average   3 = Poor

This table is not prescriptive and should only be used as a rough guide. Certain product requirements (e.g. use in extremely hot temperatures) will take priority over certain elements within the table, although when designing for disassembly it is important to know the options available.

Virtual Disassembly

This is currently being developed to quickly and accurately simulate the disassembly of products. When combined with the use of human-interaction peripherals (motion trackers, data gloves, Anir mice), the disassembly of complex constructions can be carried out prior to building test models, and improvements/modifications can subsequently be added there and then. The path for disassembly of products can be monitored in 3D, as well as timed. 3D CAD models are taken as inputs, assembly relations are established and the possible motion paths are generated.

Design for Active Disassembly

Active Disassembly involves the disassembly of components using an all-encompassing stimulus, rather than a fastener-specific tool or machine. When designing for active disassembly, we tend to consider the use of smart materials which undergo self-disassembly when exposed to specific temperatures. Shape Memory Polymers (SMPs) and Shape Memory Alloys (SMAs) form the majority of the smart materials used. Often in the form of screws, bolts and rivets, AD fasteners change their form to a pre-set shape when exposed to a specific trigger temperature, which can range from approximately 65 degrees Celsius to 120 degrees Celsius, depending on the material. Taking the example of the screw – the thread disappears when exposed to the trigger temperature, allowing it to fall naturally out of the cavity without any extra stimuli. In some cases an AD sheath is used around a traditional screw where structural integrity or costs are a significant issue.

Designing for Active Disassembly takes into account both the product architecture and fastener selection. It is important to consider how heat will be applied to the fastener (i.e. radiation, convection, conduction), and collection of the fasteners when they have been removed from the assembly. If it is not possible to locate the fasteners externally then it may be worth considering a conductive element which allows heat to be transferred directly to the fastener. When considering fastener collection it is ideal to make the axes of fastener insertion co-planar. Physical component separation using SMAs will require some thought towards tolerances and the forces that are required to separate joined components. As with any product incorporating AD materials, a mock-up or prototype will allow the manufacturer to determine the optimum level of separation, trigger temperatures, size and number of fasteners, as well as the method of heat application.

Summary of DFD Techniques

The actual period when the product is used by the consumer could be seen as a small step within a fast-turning product life-cycle, so the key to successful DfD lies in maintaining flexibility within assemblies, easy component separation and easy access to parts. To summarise:

- Choose recycling-compatible materials (as far as possible).
- Avoid using materials which require separating before recycling (re-use is OK, subject to performance testing).
- Use as few components and component types as possible (without compromising the structural integrity or function of the product).
- Integrate components (which relate to the same function) where possible.
- Standardise the use of fasteners – use commonly available parts and maintain consistency within the design.
- Make components easily separable.
- Apply non-contaminating markings (e.g. through etching or moulding) to materials for ease of sorting.
- Maintain good access to components and fasteners. Consider making the plane of access to components the same for all components.
- Do not paint plastic parts or other coatings which may contaminate other plastics when recycled.
- Consider the use of ADSM technology for non-temperature-critical products.

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