ABSTRACT

METRICS FOR ESTIMATING THE PRODUCT DISASSEMBLY EFFORT

by
Pradeep Kumar Yedlarajaiah

The concepts of environmentally friendly manufacturing and ecological reuse of materials have resulted in an increase in the number of disposed products that are disassembled. Moreover, the imposition of EPA regulations is forcing companies to invest in methods for protecting the environment. The first strategy in this vein is material recycling. The issue of recycling became important because of the limited landfill space, diminishing natural resources, environmental pollution due to dumping of products containing hazardous materials. Likewise, it is projected that the cost of extracting materials from natural resources is going to be much more expensive when compared to reclaiming materials from disposed products.

The above issues bring to light a new concept called demanufacturing. Demanufactuing includes product disassembly, part reuse and remanufacturing and material recycling. Originally the presence of precious metals in the products made companies to opt for recycling, but the present industry feels that it is possible to have demanufactruing for all product types. In order to recycle or reuse the product one has to perform the operation of disassembly to see what components can be reused and which can be sent for either recycling or disposal. In addition, one has to check the components that are going to disposal for their hazardous nature. Hence the concept of disassembly is very important when recycling is the opted choice.

Today, industries are trying to implement disassembly lines at their sites similar to that of assembly lines. Before disassembling, one has to consider the cost of disassembly as there is no definite science or technology available when compared to that of assembly. So the issue of cost of disassembly is making the industry develop some tools which help them quantify the operation of disassembly.

Keeping the above issues in concern, this research focuses on developing the theory related to disassembly processes similar to that of assembly processes. The different disassembly processes that are dealt with in this research are Adhesive separation, Chemical dissolution, Cutting, Crushing, Shearing, Shredding and Smelting. These processes are similar to the conventional processes used in the manufacturing industry though the difference lies in the manner the product is handled and the tools required for disassembly in demanufacturing industry. All the above processes are based on some metrics, which will help in evaluating or calculating the disassembly effort. The different metrics that are used in effort estimation are time of disassembly, tools required for disassembly, force (machine/human), accessibility, fixture, any instructions necessary before starting disassembly and risk factor involved with getting hurt (hazard) while the disassembly operation is being performed. The other contribution of the research consists of the development of a generic software tool, which would help to deal with strategic points of focus and also the termination of disassembly operation to maximize revenue.

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by
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This thesis is dedicated to my

beloved parents and other family members

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CHAPTER 1

INTRODUCTION

1.1 Background

The improvement of technology or automation in the field of manufacturing and assembly has led to the development of many products with varied designs that suit the convenience of different classes of society. In many cases the combination of design complexity and material complexity make the products difficult to dispose of in an environmentally friendly manner. But the public awareness of a fragile ecology is constantly growing these days and the traditional assumption that the cost of ecological burdens should be shared by society as a whole is no longer accepted [1]. Manufacturers and researchers of present world are under pressure to reclaim as much as they can from disposed products and also to produce new products that are easy to disassemble at the end of their life cycle. The reasons for such development are the rules and regulations laid by Environmental Protection Agency (EPA), disposal of hazardous materials/waste, limited landfill space, the resulting scarcity of natural resources and raw materials.

Keeping in view of the above issues, the industrial paradigm of the present world is the initiation of numerous research activities in the environmental impact assessment. Originally the value contained in any product was not recovered to its full extent at their end of life of the product [2]. Mostly ferrous metals were recovered after shredding the entire product and the rest was disposed which presently is causing the shortage of landfill space. To preserve the health of our environment, researchers brought to light the concept called 'demanufacturing', which includes disassembly, reuse, remanufacture and recycling. Re-using manufactured goods by recycling material and parts is becoming increasingly important especially in industrialized society and as a result significant efforts are made to design goods for easy recycling after their intended lives [3].

Now-a-days it is thought that these environmental strategies are going to become minimum admission to the global economy [4]. Currently most of the companies are starting their own recycling centers so that they can reclaim most of the materials for further use. Moreover, the value of preserving the environment and our natural resources may soon predominate the cost of recycling so we can expect to face growing demands for the disposal of old products in a constructive way [5].

For that reason one has to dismantle or disassemble the product into its components to dispose the products in an environmentally safe manner. Disassembly of used products is needed in order to make recycling economically viable in the current state of the art of reprocessing technology thus avoiding the future high disposal costs [6]. The applications of disassembly are numerous and extend to almost every industry that deals with discrete parts and products [7]. Almost all the companies are trying to implement disassembly centers similar to that of a manufacturing division where by trying to reuse, remanufacture and recycle the worn out products and hence 'Closing the Loop' of materials and components after usage.

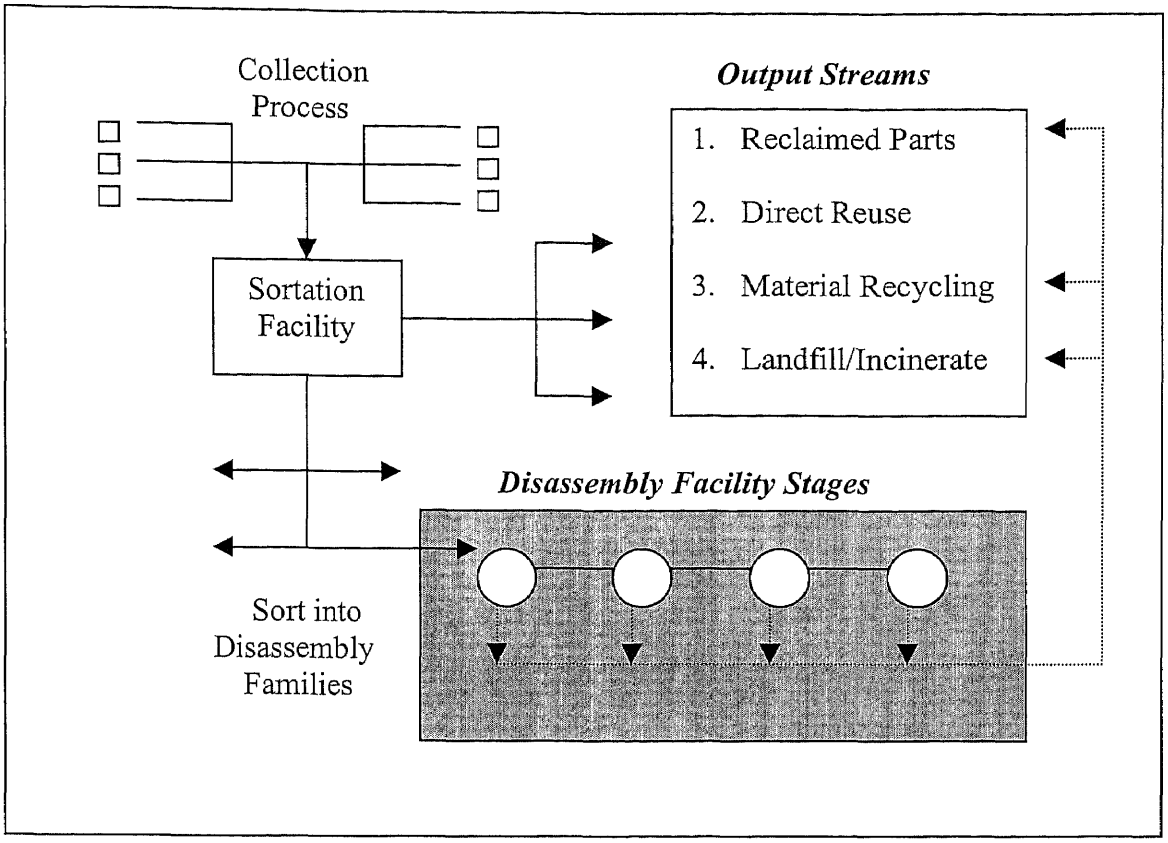

Figure 1.1 The Disposal and Disassembly Process

1.2 Aims and Objectives

The purpose of this research is to bring to introduce the concept of product disassembly and document its associated mechanics. The objective here is to develop the science of disassembly similar to that available for both manufacturing and assembly. The science of disassembly consists of using the same manufacturing methods like shearing, crushing etc in dismantling the worn out products so that one can reuse, recycle and remanufacture the components and precious metals contained in them and also to develop the metrics of disassembly like the tools required to disassemble, the accessibility of the part or fastener which is to be removed and the type and amount of force required to disassemble the product into its components. These metrics will enable to calculate the total effort required to take apart a product into its components. This effort in turn will be used to analyze the total time it takes to disassemble and hence determines the total cost of disassembly. Another objective is to develop a generic software tool, which will be useful in finding out the revenue generated by disassembling the product in consideration along with the amount of time it takes to disassemble and the different types of tools.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Now, more than ever, the issue of environmental compliance and pollution prevention is becoming important in industry. Even the public has become more aware about the solid waste generated from the manufactured products and its influence on the environment. As the cost of pollution prevention is going on increasing, the production of environmentally benign products is now both a business and technological issue, not simply a mission for the environmentalist movement [8]. The effects that cause environmental pollution occur at all stages of the life cycle of a product, right from raw material acquisition till the end of life of the product.

As the environmental pollution and the public concern is growing it is not preferable to dispose the product at the end of its life but to try to reuse some components as there are always some reusable components present in them. The management must recognize the importance of integrating environmental goals into corporate culture and necessary environmental issues must be given due consideration. After a joint research, government and industry came out with a solution called DFE (Design for Environment). This solution is supposed to be of good help to industry to prevent the ongoing harmful effects on the environment. Even though several factors like legislation, public pressure, international standards are instigating interest in DFE, the primary drivers are the costs and liabilities caused by hazardous materials and pollution [9].

DFE is the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle. DFE requires the coordination of several design and data based activities, such as environmental impact metrics, design optimization including cost assessments [10]. LCA (Life Cycle Assessment) is one option of implementing DFE. LCA is defined as an objective process to evaluate the environmental burdens associated with a product, process or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to evaluate and implement and opportunities to effect environmental improvements [11]. LCA has been and continues to be developed as a tool to systematically measure and assess any environmental impact attributable to a product.

There are many benefits of implementing DFE for safer and cleaner factories, worker protection, reduced future costs of disposal, reduced environmental and health risks, improved product quality at lower cost, better public image and higher productivity. It is also believed that DFE can solve problems associated with international standards compliance. For example, just as ISO 9000 became a de facto international standard for quality, the ISO 14000 environmental standards may soon become de facto international specifications for environmental aspects [9]. DFE not only benefits the industry environmentally, but also reduces cost and liability while increasing customer satisfaction. While DFE is one approach to ameliorate environmental problems associated with use or disposal of a product, it is not independent by itself and consists of many other approaches like solid waste management, design for recycling, design for remanufacture and also design for disassembly. The following sections will explain about the behavior of the above mentioned approaches.

2.2 Solid Waste Management

Wastes are generated practically in any industry in one way or the other. In the present era, the amount of waste generated is enormous and has attracted lot of attention. Currently waste disposal costs no longer prove to be cheap because of the hazardous content present in them and also the scarcity of landfill space. Waste produced by U.S. industry during raw material extraction, material processing and product manufacturing is somehow less visible but potentially more serious. Industry generates approximately 700 million tons of hazardous waste and some 11 billion tons of non-hazardous solid waste each year. Figure 2.1 shows that the manufacturing industry has the most responsibility for the total solid waste in the U.S.A. (about 11.7 billions).

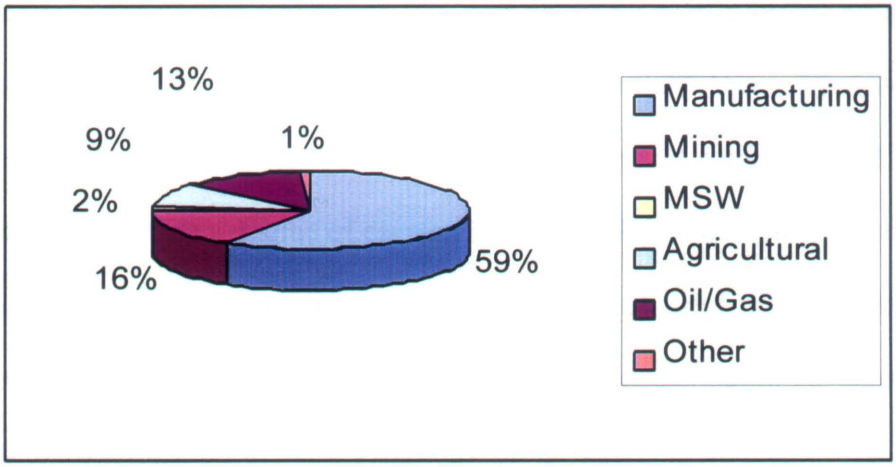

Figure 2.1 Distribution of Non-hazardous Solid Wastes in the U.S.A. (1990)
[Source: 12]

The solid waste management hierarchy is often cited as a means of justifying the desire to process solid waste by any means other than landfill.

Solid waste management hierarchy

- Waste minimization at source
- Re-use
- Recycle
- Incineration with energy recovery
- Incineration without energy recovery
- Landfill

The hierarchy places alternative waste treatment options in a fixed order of preference with waste minimization at source as the most environmentally preferred option (least environmental impact) and landfill as the least environmentally preferred option (most environmental impact). While the solid waste management hierarchy serves a useful purpose, many have come to argue that the hierarchy should not be viewed as fixed and that one should exercise a degree of caution before coming to any immediate conclusions as to what represents the most environmentally preferred solid waste disposal practice. There are of course always exceptions to the rules and depending on the scope of a given study, waste minimization at source may not be preferred if savings at one point in the system give rise to greater losses elsewhere [11].

The two practices of solid waste management are Landfill and Incineration. The best site for landfill is generally one with a natural clay base, which will aid in the prevention of groundwater combination. Landfill process may be implemented by area fill, trench fill and modified area fill methods. There are four main environmental problems associated with landfill operations: gases, nuisance, loss of farmland, and leachate. These will result in contamination of ground water and also result in the formation of acid rain. Depending on the composition of the waste that is burned, incineration can reduce the volume of waste by 70 to 90 percent. Presently, most incinerators are equipped with an energy-recovery system. This is used to capture the heat released during combustion and convert it to steam or electricity. One of the major disadvantages of incinerators is that emissions from incineration contain cancer-causing substances, such as mercury, dioxins and ash. Despite the negative effects of incineration, converting waste to energy is still the most clean process and conserves resources better than landfill methods [12].

2.3 Material Recovery

As a rule, the protection of the environment requires the reduction of waste and good management of available natural resources. Once the product has been used by a consumer and it has fulfilled its intended purpose, it has to be discarded. The worn out product may be disposed, composted or recycled. Material recovery is defined as an opportunity to reclaim post-consumer products for recycling, remanufacturing and re-use. Disposal of the product is just sending it to a landfill, which is not recommended as a good solution as it leads to pollution. Composting is the controlled, biological decomposition of organic materials into a relatively stable humus-like material. Recycling process tends to process the old parts to new raw materials and later to rebuild a new product out of them. Recycling is the only solution, which decreases the amount of waste entering the landfills and also reduces the extraction of virgin or raw materials.

Recycling reduces the amount of pollution that occurs from incineration. Recycling is considered to be the best method of material recovery. This process aims at closing the loop of materials and components after usage by reusing them for new products. Recycling is a very broad term as it consists of other terms like reuse, repair and remanufacturing. The remainder of this section discusses the different material recovery approaches.

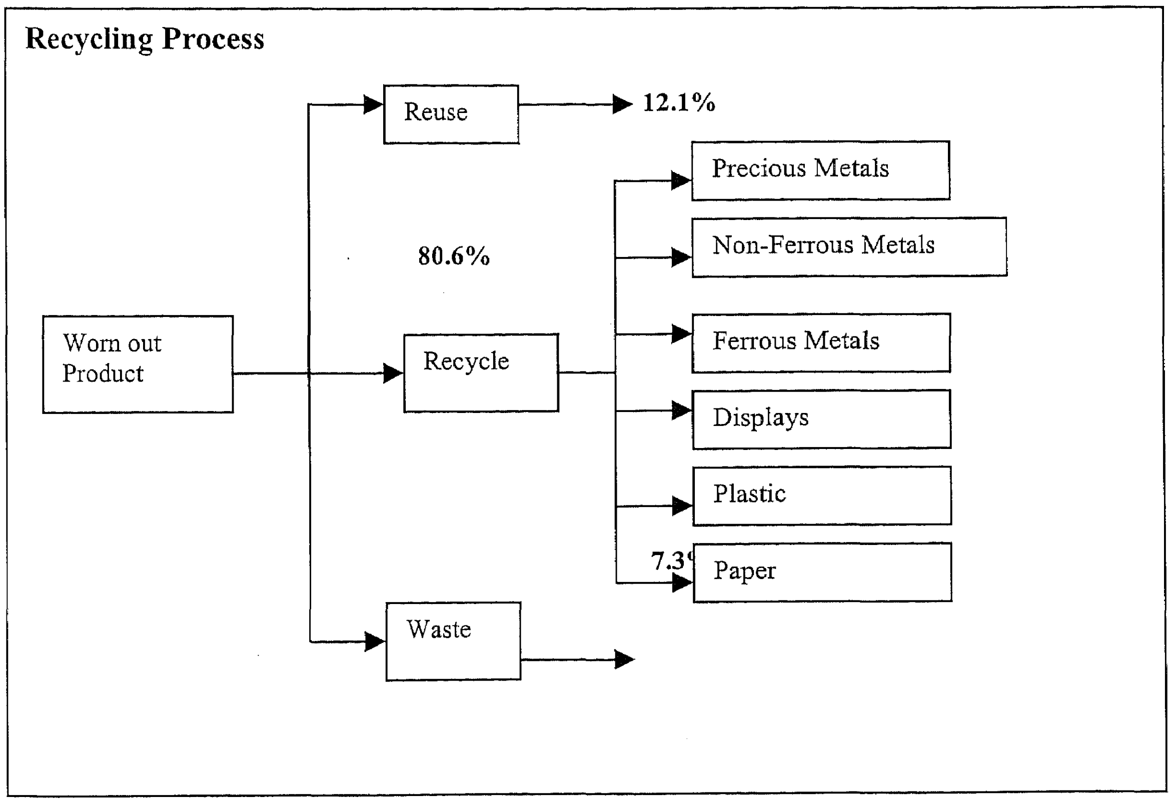

Figure 2.2 Recycling Process Streams
Source [13]

2.3.1 Reuse

Reuse is the additional use of a product after it has been retired from its original intended use. In order to reuse a product one may perform the operations like repair, cleaning or refurbishing to maintain integrity. All parts of the products should be reused in such a way that the value of new products, new components, raw material or energy it substitutes reaches its highest value. The value of a component for further usage is limited by two factors: Technical capability and market conditions. The technical capability for further usage is restricted by wear, material fatigue and damage. As to the existence of markets, it is only possible to make predictions regarding the usage as a spare part for repair or production of the same product. The possibilities of "using on" for different purposes are numerous. Currently, reuse of metals without loss of quality is profitable, provided it is not polluted with harmful alloys where as for plastics and other organic materials, the cost of cleaning, purification and reprocessing exceeds the production of a new material [2]. Reuse of parts, components or even products is often considered to be the most efficient recycling path among all.

2.3.2 Remanufacture

Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled parts from a specific product are not kept with that product. Rather they are collected by part type, cleaned, inspected for possible repair and reuse. Remanufactured products are then reassembled, using those recovered parts and new parts where necessary. The newly assembled product must be equivalent in performance and expected life to the original or a currently available alternative.

The different steps involved in a remanufacturing process are:

- Check in
- Disassembling
- Inspecting

- Sorting
- Cleaning
- Reconditioning
- Reassembling
- Control and Testing
- Packaging

It is not necessary to follow the above listed order but depends on the needs of the factory. Out of the above listed steps disassembling is the most important stage as the time and ease of disassembly are the keys to earn or loose money in the remanufacturing process. More precisely, if a product needs a long time and a lot of operation to be disassembled, the cost will increase [14].

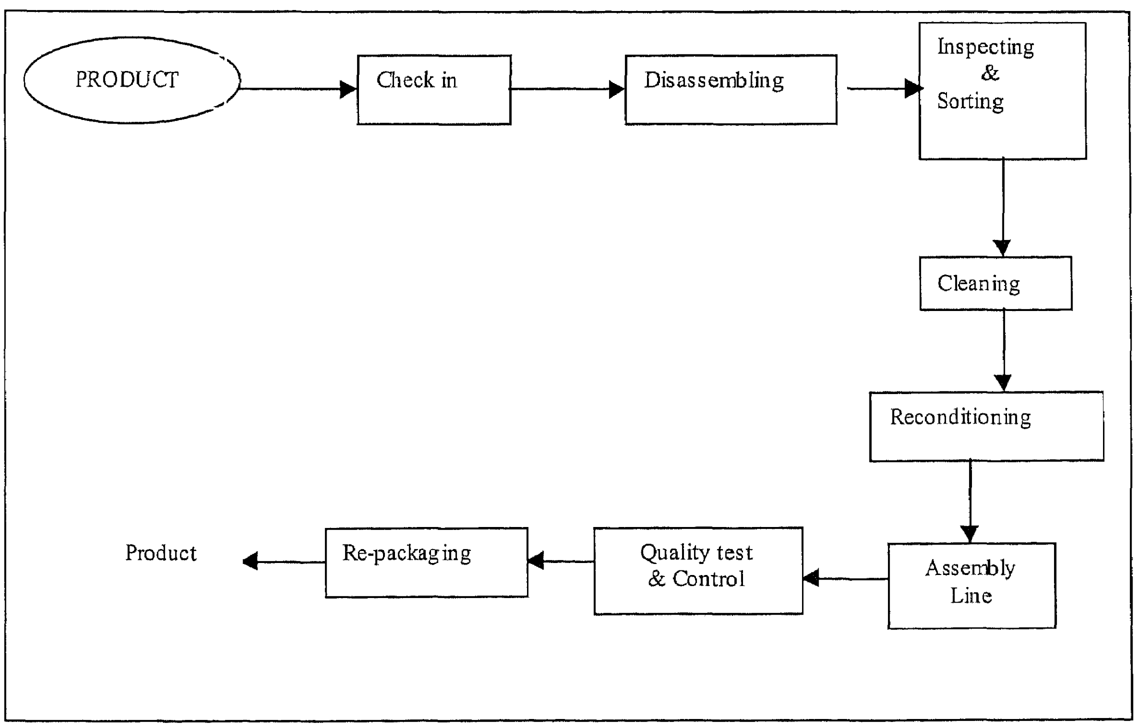

Figure 2.3 Remanufacturing Process Chart
Source [14]

2.4 Design for Disassembly

2.4.1 Introduction

Demanufacturing is an end-of-life management option for an environmentally sound and economic disposal of any product. Demanufacturing can be defined as the process of collection, disassembly, testing, cleaning and separating for reuse, or reengineering valuable materials at the end of life of any product. Out of the above listed steps present in demanufacturing, disassembly is very important. With the emergence of environmental design initiatives such as 'environmentally-conscious manufacturing', 'design for environment' and 'green engineering', design for disassembly has become an integral part of enhancing product designs to facilitate servicing, recycling and remanufacturing efforts [15]. So this chapter deals with the concepts and implementation of disassembly approach to minimize the environmental burden and maximize the revenue at the end of the operation.

Disassembly Engineering is the systematic process of physically separating a product into its parts or subassembly pieces, with the aim of reusing, recycling, incinerating or disposing. The aim is to protect the environment and to regain the value added to products. Disassembly also helps in avoiding future high disposal costs imposed by laws of legislation. Traditionally product disassembly was only done to service or repair a part. But, the disassembly of a product at the end of its useful life is slowly growing into a common and worthwhile industrial practice. One thing to be noted is that design for disassembly does not have a direct link to environmental impact, while it may increase the likelihood of recycling and therefore less waste, it is an indirect link to environment. Disassembly may be either selective or complete. In selective disassembly, one is interested in only some of the components, which have reuse or resale value and the disassembler will not care if the rest of the product gets damaged while trying to remove the required parts or components. For example in the disassembly of a car someone is interested only in the motor or transmission part of it but not on other parts of the car. In a complete disassembly all parts are separated from the product until the revenue is going on increasing and if the revenue stops at some point the disassembly is also stopped. Sometimes selective disassembly is also called as destructive disassembly where as complete disassembly is called as nondestructive disassembly.

Earlier, scrap metal dealers had recovered metal components from old equipment using a relatively crude process to crush and shred products, sending the metal for remelting and the fluff to landfill. Design for disassembly strategies have not become widely accepted in practice, possibly because of the uncertainty about how they relate to strategies for Design for manufacture and assembly [16]. It is difficult to gain all the information necessary to plan the product for disassembly. Parts or components of the product might have been modified during repair, and wear can make joining elements difficult to remove, which indicates that most of the consumer products are not designed for ease of disassembly.

Disassembly is currently labor intensive and the overall economics is still not understood while implementation of automated technology is under research. Product designers are also rarely concerned with the disassembly aspects of the product. Consequently, disassembly tends to be an expensive process and not a viable option at the end of life of the product, unless disassembly guidelines are taken into consideration during the design stage. The research to date on disassembly does not focus on the issue of cost of disassembly, which happens to be a major issue at the corporate level to jump into disassembly operations. The lack of an effective approach for estimating the end of life of a product disassembly effort is one of the primary reasons limiting a more widespread interest in product disassembly. As a result, products with a good number of reusable/recyclable parts are disposed off or recycled in their entirety. Clearly, product disassembly is important both from an environmental perspective and a corporate strategy. Keeping in view the above problems, this thesis focuses on the issues that bring in concepts to ease product disassembly and also on the metrics of disassembly process which help the user in maximizing the revenue at the end of disassembly operation. The following figure shows several basic guidelines that concern the product in a global aspect.

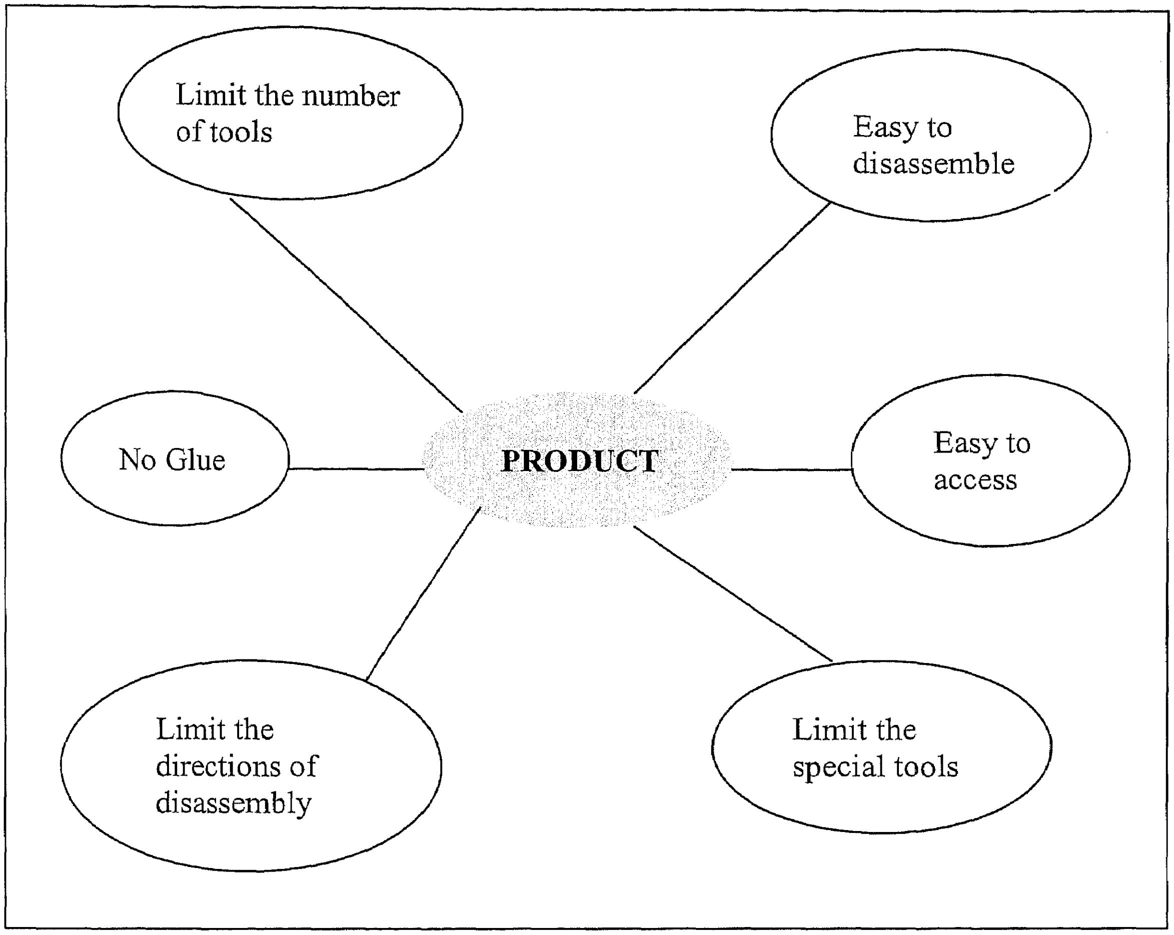

Figure 2.4 Disassembly Process
Source [14]

2.4.2 The Disassembly Process

Design for disassembly is a building block of the DFE system. It performs the design or redesign of products so that a higher percentage of the component parts can be reused or recycled. As the disassembly process is the precursor of a chain of other recovery production steps, the disassembly system should be feasible with respect to criteria related to costs, energy use, environmental burden and so on. Disassembly is a collective term consisting of disassembly sequence planning, disassembly operations planning and disassembly evaluation. Disassembly evaluation models intend to assess a product on the basis of time required to disassemble it. Disassembly sequence is defined as the order in which the components are disassembled. Before starting the disassembly operation it is necessary to choose some criteria for selecting parts and subassemblies to be recovered. The following figure illustrates the criteria that can be used before starting the disassembly

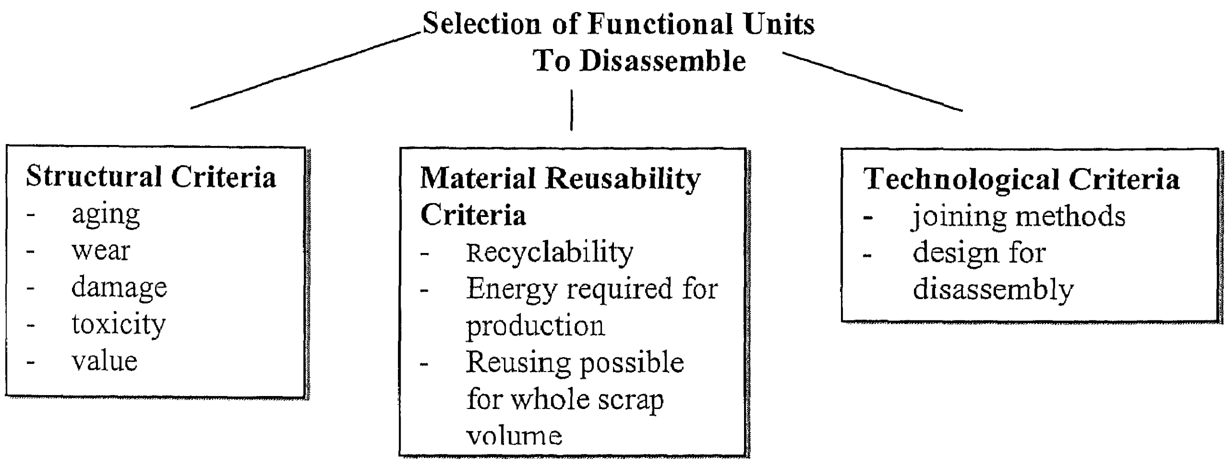

Figure 2.5 Selection criteria for parts and subassemblies to disassemble
Source [6]

It is very important to decide when to stop disassembly, as it is not worthwhile to disassemble completely into its individual components. Ideally one should disassemble as little as possible, and process large clumps for effective reuse or recycling. There are many criteria that might be used in deciding when to stop disassembly. For example, the point of maximum profit or minimum loss might be selected. A better alternative is to stop disassembly when the highest rate of profit is achieved. The highest rate of profit obtainable for the larger appliance is after the removal of only a few critical items. One has to consider the environmental factors also in deciding when to stop disassembly. Generally, a compromise must be made between environmental impact and the profit return.

This thesis visualizes disassembly as a multi-step process or plan. At each step one or more parts with certain common properties are removed. The separated element could be a partial part, an entire part, or a sub-assembly of parts. This removal process and its associated logistics are the primary determinants of the disassembly effort. A separated subassembly may be further disassembled; hence a diverging network represents the disassembly plan, with some steps occurring in parallel. The separated parts or subassemblies may go to any of the output streams like reclaimed parts, direct reuse, material recycling and landfill or incinerate. For a given product multiple plans can be generated each having a different return on investment. It should not be assumed that disassembly is just the reverse of assembly process.

A disassembly plan is described by the sequence of processing steps, the part or parts worked on each step, and the part portions, parts and subassemblies remaining at the end. Usually, as we progress down the disassembly plan three phases are observed. In the first phase, the disassembler attempts to improve the accessibility to different parts of the product, as a result no value is directly released in this phase. In the second phase valuable parts and subassemblies are reclaimed. Finally, in the last phase separation is done so as to facilitate down stream material recycling processes. Often a disassembler will discard the product after phase two, with the knowledge that the marginal cost benefit of further disassembly is not attractive.

2.5 Research Need and Purpose

Wide diffusion of consumer and electronic goods and shortening of product lifetime have given rise to an increasing quality of used products being discarded. The commonly discarded products include like cars, household appliances, consumer electronics etc but it is expected that computers would be discarded at a faster rate in future due to their rapid obsolescence rate [6]. The most evident issues concerned with this are as follows:

- The large quantity of waste generated creates a landfill problem. It is assumed that presently half of the landfill capacity is being used and in the upcoming period the cost of disposal is going to increase rapidly.
- The manufacturing waste generated contains lot of hazardous materials like lead, cadmium, which pose a serious threat to the environment.
- The present industry is producing the products, which are made of different material compositions that are not readily biodegradable.
- The technological developments within the manufacturing industry have not been paralleled by the recycling industry. There is a lack of technology to handle the complex products which are disposed off today and hence the recycling is limited only to ferrous and very few non-ferrous metals.[6]
- The other concern is related to the diminishing natural resources.
- Finally, today there is a strong incentive towards recycling of discarded complex products because the intended legislation includes the obligation to recollect and upgrade the discarded products in an environmentally conscious way.

In context of the above issues, the present industry is facing substantial problems in terms of end-of-life of products. The above problems propose a definitive need and in depth research in the area of disassembly for environmentally conscious recycling. In the present era most of the literature availability relates only on developing environmentally benign products but little on the existing worn out products. The purpose now is to consider different ways a product can be recycled which is environmental hazard free. To dispose a product such that it is not harmful to the environment one has to perform disassembly operation on the product to remove the hazardous components. As stated earlier about the impending scarcity of natural resources it is clear that recycling will become the dominant resource for metals, as the effort to regain metals from scrap will be less than the effort used to extract them from the ground [2]. Hence the concept of Disassembly becomes important related to safe disposal of products and also to recover useful and precious materials from the products.

CHAPTER 3

DISASSEMBLY PROCESSES

In today's demanufacturing industry there are no specific processes that are used for disassembling the products and the way the operations are performed in one industry totally differ from the other. But if the processes in the manufacturing industry are taken into consideration, the processes are specific and the present industry has the knowledge about all of these processes. Once the specific processes are established the theory related to each process can be explored and hence made use of in the respective industry. Since there are not any established processes as of today in the demanufacturing industry it becomes necessary to concentrate on the development of disassembly processes. When one talks about disassembly processes it is not necessary that these have to be something new but it may also be thought of about the same processes that are used in the manufacturing industry and trying to link to disassembly. Hence disassembly processes are those which will ease the disassembly operation and reduce the effort involved in the operation.

Disassembly processes differ when compared to conventional processes as the parameters involved are handled differently. For example, in a conventional process to join two parts one has to apply some amount of force but in order to remove or separate the two parts the amount of force to be applied and also its direction along with the tools involved differs completely. This depends on many issues as the wear and tear between the parts and many others. The metrics like time, tools required, direction of force to be applied differ when conventional and disassembly processes are compared. So the above issues conclude that disassembly processes are important for any demanufacturing industry.

3.1 Adhesive Separation

3.1.1 Process Mechanics

Adhesion is the force of intermolecular attraction evidences in the phenomena of wetting where in molecules of adhesive are more attracted to molecules of adherend than to each other. Numerous components and products can be joined and assembled using an adhesive, rather than most of the joining methods. Adhesive bonding has been gaining increased acceptance in manufacturing ever since its first use on a large scale in assembling load-bearing components in aircraft during World War II.

There are basically three types of Adhesives.

- Natural Adhesives. Eg: Starch, Dextrin.
- Inorganic Adhesives. Eg: Sodium silicate, Magnesium oxychloride.
- Synthetic organic Adhesives. Eg: thermoplastics or thermosetting polymers.

Because of their strength, Synthetic Organic Adhesives are the most important in manufacturing processes.

There are nearly 4 types of joints using adhesives.

- Lap joints
- Butt joints
- Corner joints
- Flange joints

The selection of adhesive depends on the properties to be met by the adherends involved in the bonding process. For this the adhesive selected contains different materials or organic compounds. This makes the product impure or the number of different materials being used in the manufacture of the product increases, making disassembly difficult.

All the above mentioned joints are very good in tensile, shear and compressive forces. So it is necessary for us to concentrate on cleavage type or peel type forces to disassemble the adhesive joints.

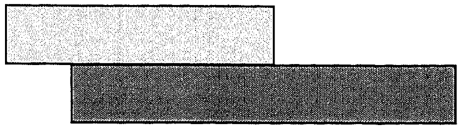

Figure 3.1 The structure of an adhesive bond

Disassembly Force

There are various methods disassembling adhesive joints like using Force to break them, Heating, Cooling to very low temperatures and applying thermal shock and using Organic solvents.

Breaking stress required in a butt joint is equal to sum of residual stress and rupture stress.

$$F = \frac{1}{\alpha}\left(\frac{\varepsilon}{\beta} - s\right)$$

Where F is the breaking stress

ε is the cohesion of the adhesive material

α is the stress concentration factor due to the difference between the mechanical constants of the adherend and the adhesive

β is the stress concentration due to heterogeneity of all solids

s is the shrinkage stress.

The total cutting force required in cutting mechanism is

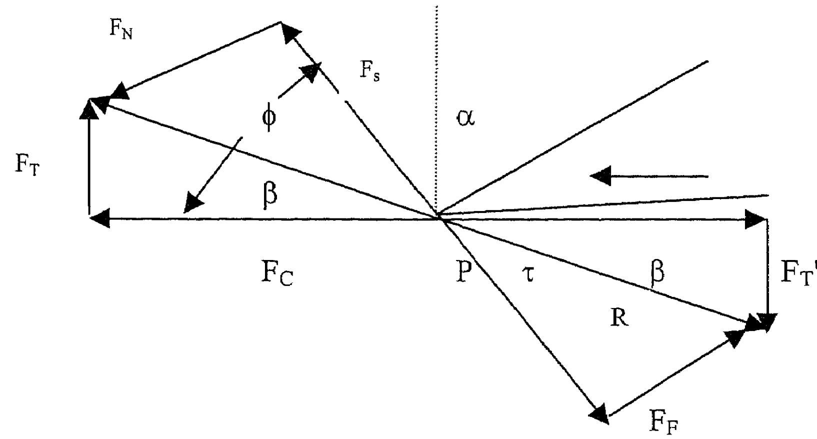

Figure 3.2 Cutting force vectors for knife stripping
Source [17]

$$H = Fc + Fz + Fi$$

$$= \lambda\omega t \ \frac{(\sin 2\phi + k\cos 2\phi)}{\sin^2\phi} + Fi$$

The peeling force is proportional to the product width of the joint and the thickness of the adhesive used in the joint.

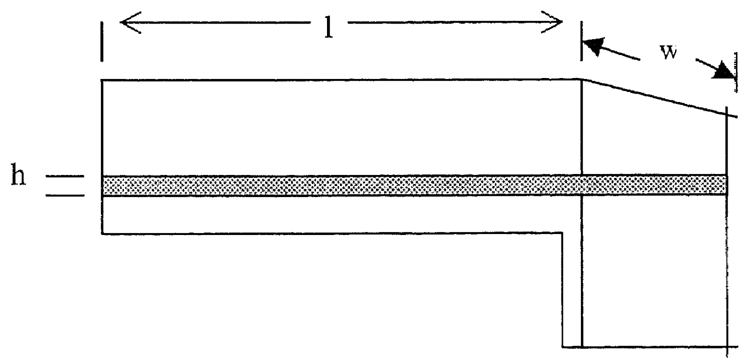

Figure 3.3 Peeling force relation

Process Variables

The force required for Adhesive separation depends on the following parameters.

- Length of overlap
- Film thickness

- Behavior of Adhesive
- Presence of Oxide film

The force F needed to split the joint increases with the length of the overlap and also the film thickness. The force required is also affected by other parameters like behavior of adhesive and presence of Oxide film.

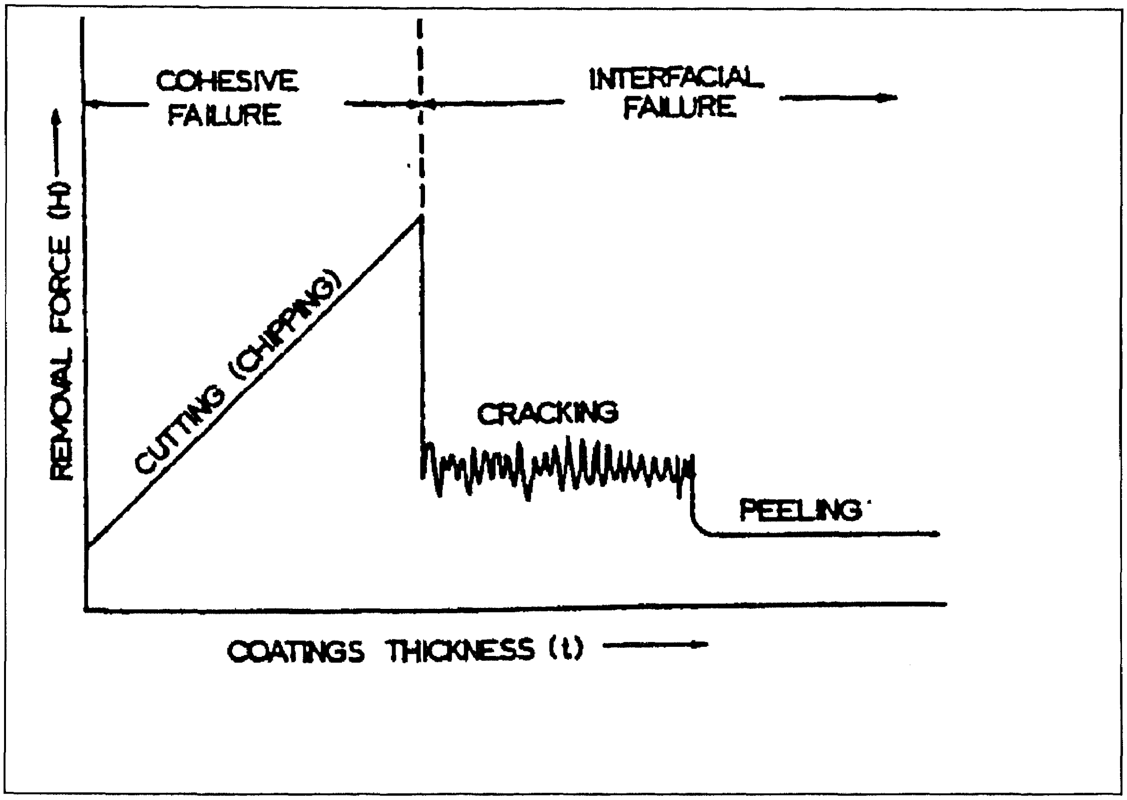

Figure 3.4 Removal forces for knife stripping

By the behavior of adhesives we mean, if it is brittle, little force is required and if it is ductile and tough large forces are required. A large force is required if a porous or thin, strong oxide film on with some roughness is present in the joint.

3.1.2 Process Examples

Adhesives can bond a wide variety of similar and dissimilar metallic and nonmetallic materials and components with different shapes, sizes and thickness to each other. Adhesives are used in applications such as sealing, insulating, preventing electro-chemical corrosion between dissimilar metals, and reducing vibration and noise through internal damping at the joints and also in applications like labeling, packaging and home furnishings. Adhesive bonding can be combined with mechanical joining methods to further improve the strength of the bond.

Major industries that use adhesive bonding extensively are aerospace, automotive, appliances, electrical, aircraft and building products. Applications include attaching rear-view mirrors to windshields, automotive brake-lining assemblies, laminated windshield glass, helicopter blades, honeycomb structures, tiles, aircraft bodies and control surfaces.

3.1.3 Process Tools

The best way to remove the adhesives is to subject them to peeling forces. The figure 3.5 shows the application of peeling forces to remove the adhesive. Blunt knife may be used to separate the adhesives by cutting operation. Otherwise techniques like applying organic solvents, ultrasonic techniques and applying thermal schok after cooling to very low temperatures can be employed to separate the adhesives.

3.1.4 Industry Practice

In any industry adhesive separation will only be carried out if the vendor requires from a high valued commodity such as aluminum or copper. Adhesive separation is not carried out on items such as plastic, metal and other lower valued commodities. The cost involved in removal of an object attached by an adhesive is too high. If labor costs are

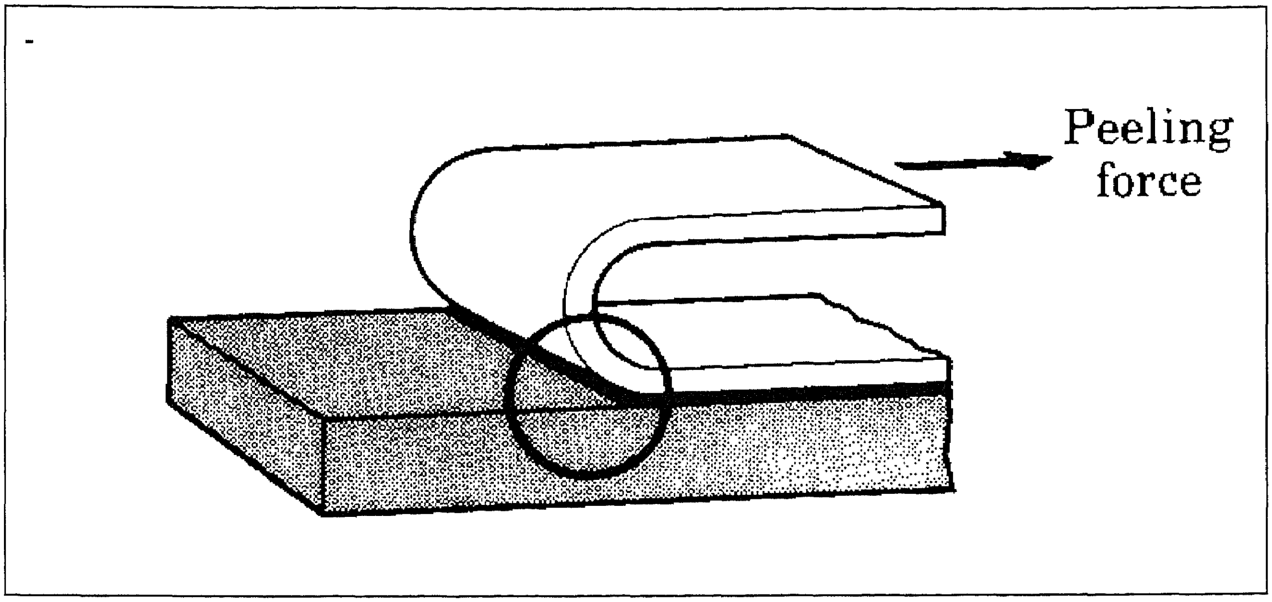

Figure 3.5 Application of peeling force on the adhesive

high the value added from removal of a label are not realizable. First of all the component attached is usually a paper or plastic label attached to a shipping box. The box vendor will allow some level of impurity, which the adhesive backed label will represent. The costs associated with removal of labels are too high to be justified by industry.

There are some instances where adhesive separation will be required. One such application is reuse of parts or components. For example disks can be reused if formatted and packaged, and sold under the category of "used". The problem is efficient removal of the label from the plastic casing. Other application involves reusing parts that have old VIN numbers and bar-coding labels that need to be updated. Such labels need to be removed.

Disk Drive label removal involves an apparatus designed at Penn State University. It consists of heating the disks, which loosen the adhesion bond between the glue, label and plastic casing. The disks then pass through an apparatus that scrapes the labels of the disks. The problem with such an apparatus is that the heat warps the disks so that the disks become unusable. The disks that do not warp have a sticky film that make it difficult to re-market. Adhesive separation technology will make the process more feasible for industrial use. It is still being investigated in industry but is slowly being used for some small applications.

3.2 Chemical Dissolution

3.2.1 Process Mechanics

Chemical dissolution is the process of removing material from the surfaces by using chemicals by converting the metal into a metallic salt due to chemical reaction.

The process of removing material using chemicals may also be thought similar to that of Selective Etching. It is selective, because we apply chemicals only at places where we need to remove the material. The surrounding areas where there is no need of removing material some sort of preventive coating called masking must be applied so that it may not react with the chemical. The amount of material removed with this method is very small as compared to various other methods.

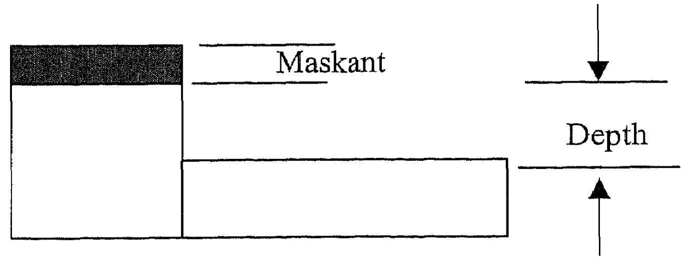

Figure 3.6 Chemical Dissolution Action

In this method the amount of material removed depends on parameters like

- Type of material to be removed
- Selection of reagent

The above two parameters are interdependent as the selection of reagent is completely depended on the type of material to be removed. The primary aim in selecting the reagent must be able to dissolute the material which is to be removed. If we select some reagent it may or may not decompose the material to be removed. Hence selection of reagent depending on the material is a very essential parameter in this method of disassembly.

Disassembly Force

In this disassembly process, there is no requirement of any force as the reactivity of the reagent with the material plays a vital role. So we are interested in the reactivity and not in the force. The faster the reagent reacts with the material to be removed the faster the disassembly is and less is the time. The rate of reactivity denotes the time of disassembly.

3.2.2 Process Examples

Chemical dissolution process is employed to remove small amounts of material from the surface of any component. This process is mainly used in operations like embossing, coining and engraving and also in aircraft industry. This process is best suited for production of printed circuit boards. To utilize the amount of copper contained on the PCB's this process is best suited.

3.2.3 Process Tools

The use of any special kind of tools is not required in this process. The tools that are used in this process are chemical reagents and etchants such as acids and alkaline solutions. The acids and alkaline solutions remove the metal by the chemical conversion of the metal into metallic salt.

3.2.4 Industry Practice

Generally Chemical Dissolution is used to remove very small amounts of material to get a good surface finish. In a disassembly removal of such small quantities of material is not at all needed, as it is time-consuming process and also not a revenue generator. But if the product that is being disassembled contains the small amount of precious metals then chemical dissolution becomes a very useful process. Such type of operations are under investigation in the present industry so that the natural resources are not used to extract these materials.

3.3 Cutting

3.3.1 Process Mechanics

Cutting is the term used to describe the removal of some of the material to reach the parts or components that have some reusable value or remove those parts that obstruct the disassembly operation. In a selective disassembly cutting becomes a very important operation to recover the reusable parts, which increases the revenue or return on investment. Cutting involves a specially shaped tool exerting a concentrated force on the work material. The effects of this are distributed in such a fashion as to cause a controlled plastic flow that results in the formation of a scrap, chip.

There are three ways of Disassembling using cutting as the process, which can be used depending on the manner we need to cut the product. The three ways are

- Through Cutting
- Edge Cutting
- Other Cutting Methods

Through Cutting

This method of cutting can be used to cut through a product. A band saw can be used for this process as shown in the figure 3.7

Edge Cutting

Edge cutting is used for cutting the product or material from one end. A circular saw can be used for this process as shown in the figure 3.8

Other cutting methods are dealt with in the end.

Disassembly Force

In cutting process, the material being cut has a concentrated force applied to it by the tool. An analysis of a single grain that is being cut from the workpiece reveals that the grain is exposed to different states of stress. Grains being cut from the workpiece move from the unstrained state up along the elastic curve beyond the yield point and into the plastic region where shear deformation, the grain is relieved of the forces acting on it and returns to an unstressed state in a deformed orientation.

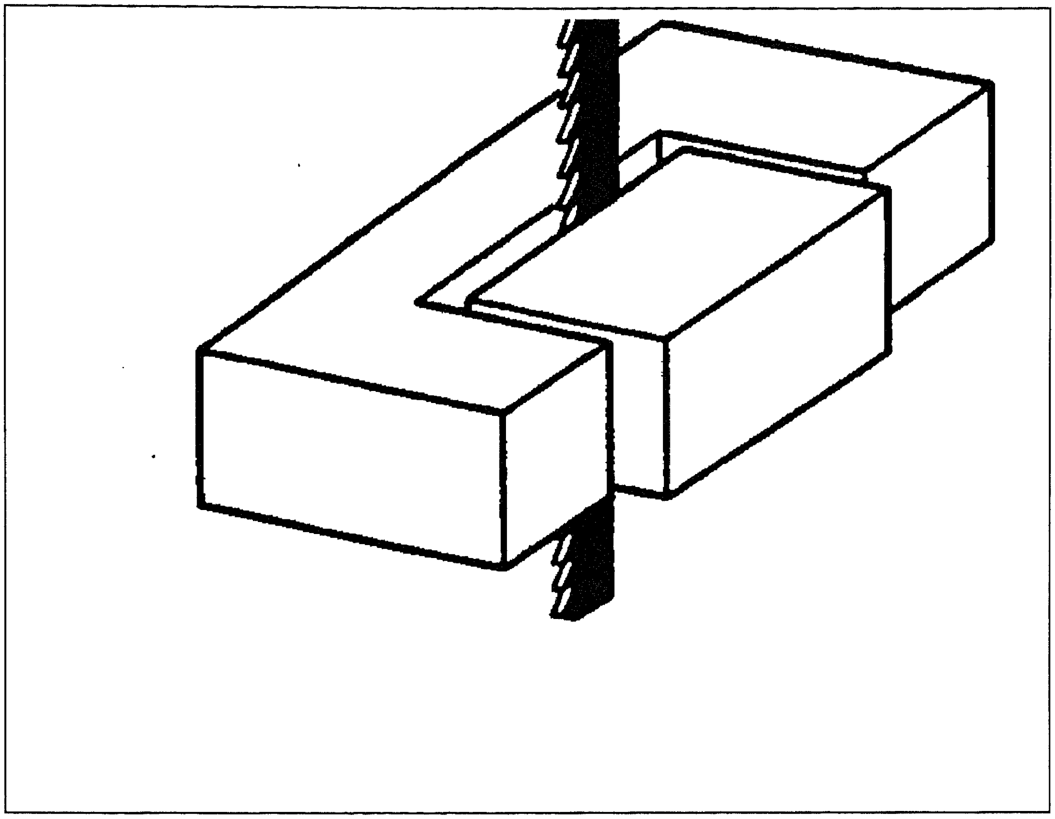

Figure 3.7 Usage of a Band saw

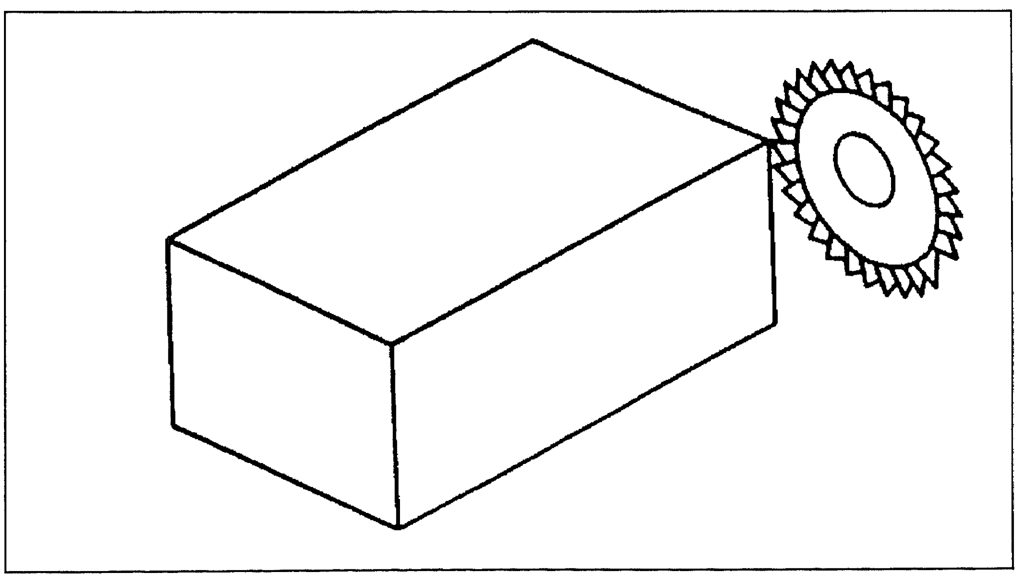

Figure 3.8 Usage of a Circular saw

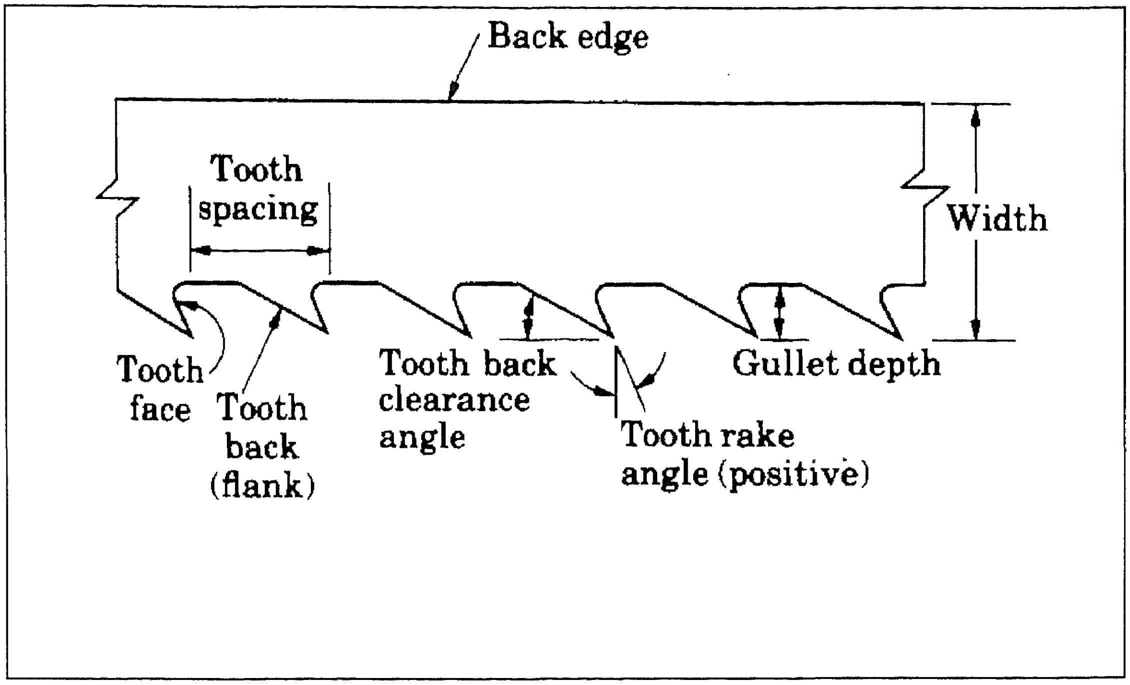

Figure 3.9 Variables of a Saw

The force required for cutting is approximated as that of broaching and the same can be found out using the following formula.

Cutting force per tooth = wSscos $(\lambda-\alpha)$ /sin ϕ cos $(\phi+\lambda-\alpha)$

Where w= width of cut (Incase of circular hole, w = circumference)

ϕ = Shear angle

λ = Friction angle

α = Rake angle

Ss = ultimate shear stress of work material

The disassembly force, which is required, depends on various factors like feed, Depth of cut, cutting speed.

Process Variables

- Feed (f)
- Depth of cut (w)
- Cutting speed (v)

The feed rate is the thickness is the distance moved by the tool in an axial direction. Increasing of feed widens the area of contact and changes the forces per unit length.

The Depth of cut is the thickness of metal removed from the bar in radial direction.

The cutting speed is the rate at which the uncut surface of the work passes the cutting edge of the tool. In sawing, cutting speeds are affected by the material, size, and cross section of the workpiece.

The rate of metal removal is given by (v.f.w)

The cutting force reduces considerably with the increase in the rake angle at normal speeds.

3.3.2 Process Examples

The examples of cutting process are varied depending on the industry or product under consideration for disassembly. For example if a computer is considered for disassembly then cutting is used to cut the wires and in case of mainframes cutting is used to eliminate the large rubber tubing's so that other parts become accessible and if an automobile is considered for a selective disassembly cutting operation is used to eliminate all the parts that are not considered for disassembly or removal so that the valuable parts are easily accessible. So depending on the industry the cutting operation differs but it is a very important operation in disassembly.

3.3.3 Process Tools

The different of tools that may be used in the process of disassembly by cutting are band saw, reciprocating saw and circular saw.

3.3.4 Industry Practice

In industries cutting operations are performed to save time and also to reach the valuable parts or components in the product. The amount of cutting within industrial practice will depend on the level of OSHA standards of safety and the types of cutting allowed by management because some disassembly shops will not allow acetylene torch cutting or large hydraulic cutting of steel because of the safety factors involved in the process. IBM uses the cutting operation to remove the large rubber tubing in the mainframes so that the valuable parts are easily accessible. PRO Auto Recyclers use the cutting operation to remove all the damaged portion of the car and this also helps them to reach the engine in a quicker time.

3.4 Crushing

3.4.1 Process Mechanics

Crushing is the mechanical process used to reduce the mass of the particles. Generally crushing is employed when the waste scrap is being sent to vendors so that the space occupied in a vehicle is reduced. The crushing process is achieved by two surfaces gripping the material between them and subjecting the material to a force by one or both the surfaces. Crushing is a process of compression where the material needed to be crushed passes through the crusher equipment and getting compressed. It is said that in compression the movements of parts of a solid under strain is a sliding one i.e., compressive action is like sliding of different layers at right angles to the direction of compression and it is this action which is responsible for breaking. Comminution is employed on a vast scale for the separation of the useful constituents and crushing is one of the processes of Comminution.

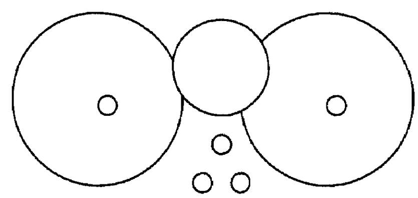

Figure 3.10 Process of Crushing
Source [18]

Disassembly Force/Power

In the crushing process, we use different type of crushers depending on the material needed to be crushed and also the throughput required from the machine. The main aim is to break the material for the purpose or recovery or reuse. So energy is supplied to the equipment which is used to break the material. Depending on the properties of the material, the stress or force must be applied to break it. The force must be applied at the stress concentration area to get the desired effect in less time.

The energy required changes as the number of stages changes. Generally the equation for energy is given by

Total deformation energy = $K \log (D_1/D_n)$

Where K = a constant

D_1= original average particle size

D_n = final size

The power required in a Jaw or Gyratory crusher is given as

(area of 1 plate) X (ultimate tensile strength) X (stroke) X (frequency)

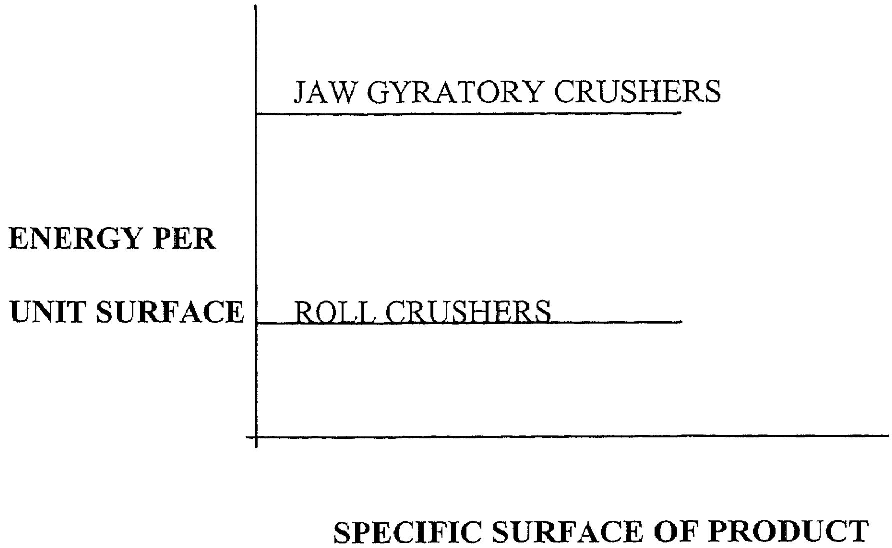

Figure 3.11 Energy per unit surface
Source [18]

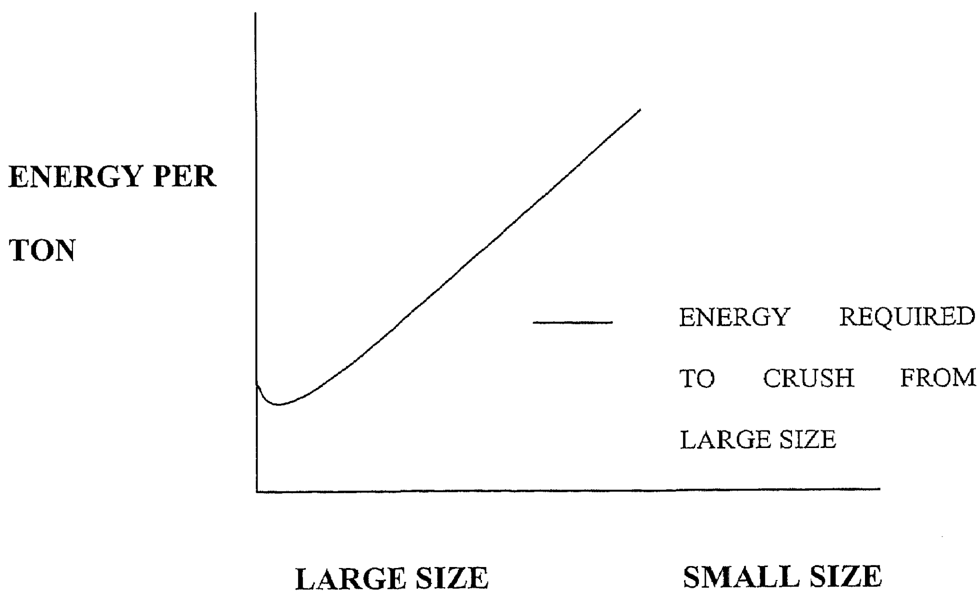

Figure 3.12 Energy required per ton from large scale to small scale
Source [18]

Process Variables

When energy is supplied, heat increases and the solid melts and adheres to the machinery. So it must be seen that the temperature is not too high. The rate of output or throughput size is depended on the size of feed and also on the physical constitution of the feed material.

3.4.2 Process Examples

Crushing as of today is not seen in many industries and at present it is mainly used to crush the fluff or solid waste at the vendor. Prototype test products are also crushed after the required tests are performed. Industry is trying to make use of this process to increase the revenue at the end of disassembly operation.

3.4.3 Process Tools

The different types of crushers used in the process are

Jaw crushers

Gyratory crushers

Roll crushers

Disc crushers

3.4.4 Industry practice

Industry is trying to use this process to remove valuable commodities from smaller products like consumer electronics. Also at most of the automobile facilities prototype automobiles, which are basically built for evaluating the performance, are crushed at the end of evaluation and try to get the valuable commodities from them. For example, in the automobile industry the sponge material from the seats is removed and the entire lot is crushed before sending it to the vendor where the sponge is made into large sheets which is used in the carpet industry. This process is still being investigated for a proper usage.

3.5 Shearing

3.5.1 Process Mechanics

The shearing process involves cutting sheet metal subjected to shear stress. Shearing is one form of cutting, which is basically used to access the reusable parts by eliminating the unnecessary material.

There are three ways of disassembling using Shearing as the process which can be used depending on the manner we need to shear the product. The three ways are

- Punch & Die shearing
- Using Chisel
- Using Scissors

In Punch & Die shearing, the product/ material to be cut is placed between a punch and die and a force is applied on the punch to shear the material which gets sheared at the joint of die.

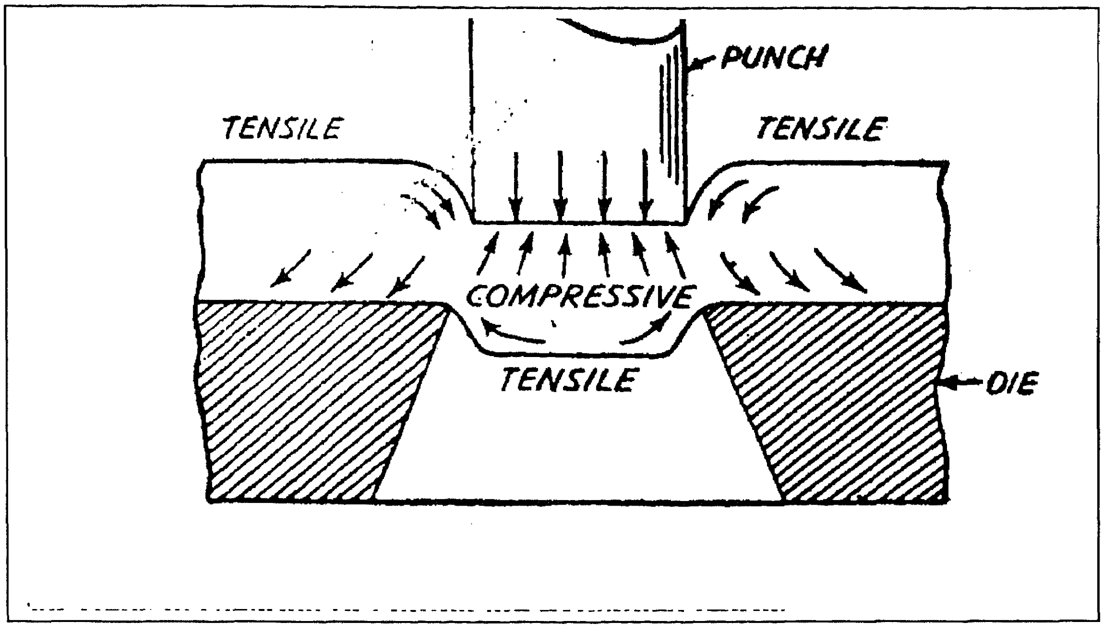

Figure 3.13 Punch & Die Shearing

In shearing using Chisel, a hammer is used to apply the force on the chisel which shears the material fixed in some vise. In shearing using Scissors, a scissors is used to cut the material by shearing it. This is limited to very few materials.

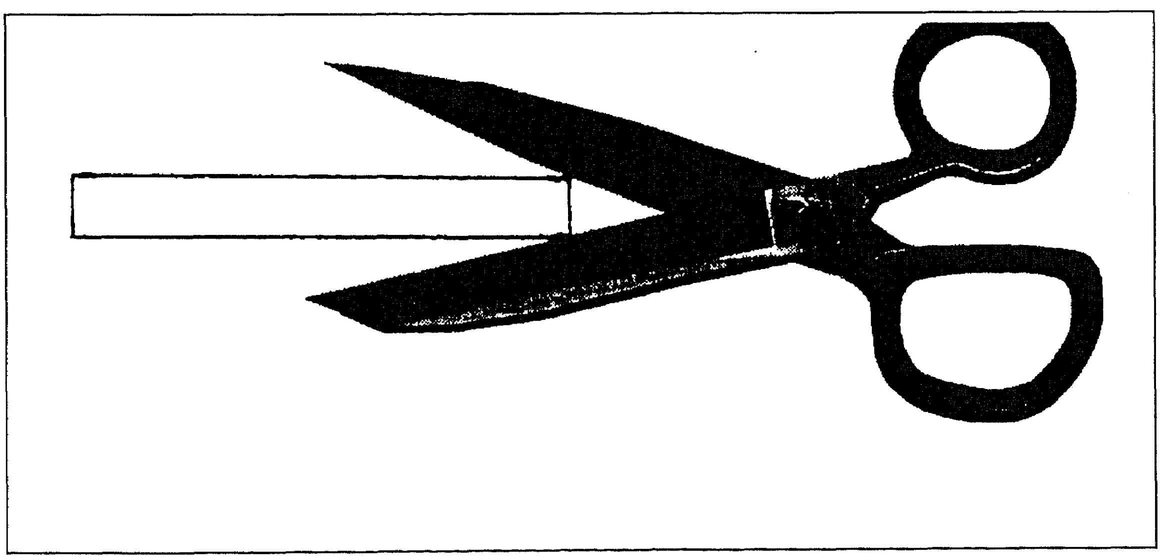

Figure 3.14 Shearing by Scissors

Disassembly Force

In the shearing mechanism, shearing usually starts from the formation of cracks on both top and bottom edges of the workpiece. These cracks eventually meet, and complete separation takes place. In general the force required for shearing can be given as the product of the shear strength of the material to be cut and the cross sectional area being sheared. In punch & Die method the maximum force required can be by using the empirical formula

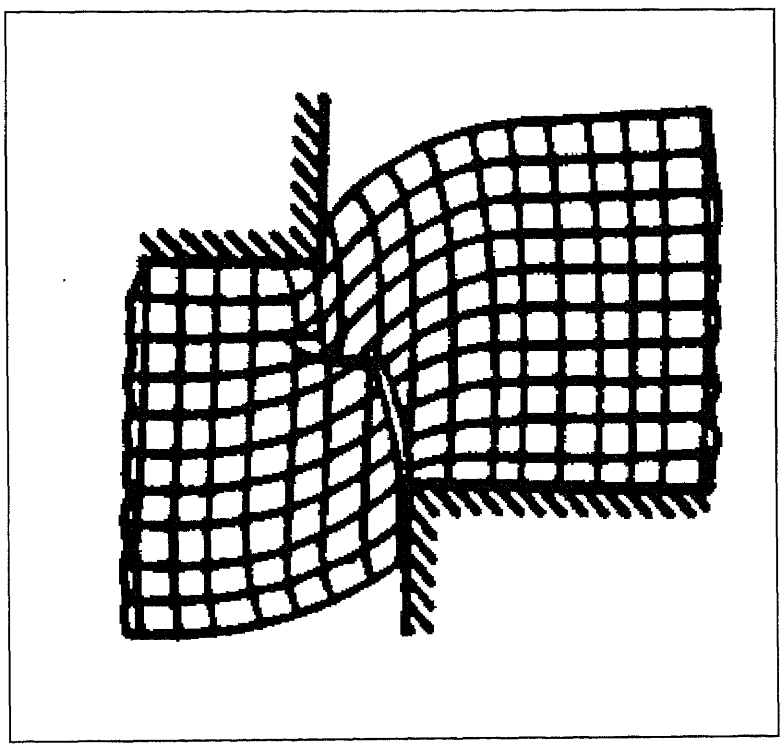

Figure 3.15 Shearing Graph

$F = 0.7(UTS)(T)\,L$ where

UTS = Ultimate Tensile Strength of the material

T= thickness

L = total length of the sheared edge.

Process Variables

The force required to complete the shearing process depends on the maximum shear strain that the material can undergo before fracture. The force depends on various parameters like

- Clearance
- Speed
- Corner radii

The clearance is between the punch and die must be adjusted exactly because, if the clearance is too large the material may undergo tensile stresses instead of undergoing a shearing deformation and get bent.

The force required for cutting operation keeps on decreasing with more clearance.

3.5.2 Process Examples

Shearing like cutting is an important operation when disassembly comes into picture. Shearing by scissors is a very useful operation to eliminate all the power connections and also if any cards in the product. At PRO Auto recyclers, shearing operation is used to remove all the power connections in an automobile.

3.5.3 Process Tools

The common tools that are used in this operation are Chisel, Punch & Die, Scissors. But out of the above presently different types of scissors are important.

3.5.4 Industry Practice

Shearing operation and cutting operation are both similar but the way the force is applied makes the difference between the two. The most common use shearing operation involves the cutting or removal of wires by scissors. This is carried out in many disassembly facilities such as computer disassembly, automobile disassembly etc. Shearing and cutting are most used operations in disassembly.

3.6 Shredding

3.6.1 Process Mechanics

Shredding is the term used to describe the mechanical process of particle size reduction, using a shear cutting process. Many facilities for the recovery and reuse of solid waste require that the waste components be physically separated from each other and that a reduction in the particle size of the waste precedes recovery operations. Shredders have thus become a common process, in particular, for metal recycling operations.

Shredding equipment is typically a single or dual rotor machine, with rotating shear blades as shown below. As the particles pass through these blades, they are gradually broken into smaller pieces. As the entering solid waste will be of different sizes, the desired output particle size and throughput rate are important criteria in selection of the appropriate shredder. Shredders could therefore be as small as tabletop equipment, to those that are over fifty feet tall. A kitchen blender represents the simplest and smallest type of a single rotor shredder. Industrial shredders tend to be setup in stages, where the particle size is sequentially reduced as it based through each inline shredder. This is illustrated in the figure below. The shredder is usually vertical with a gravity feeder.

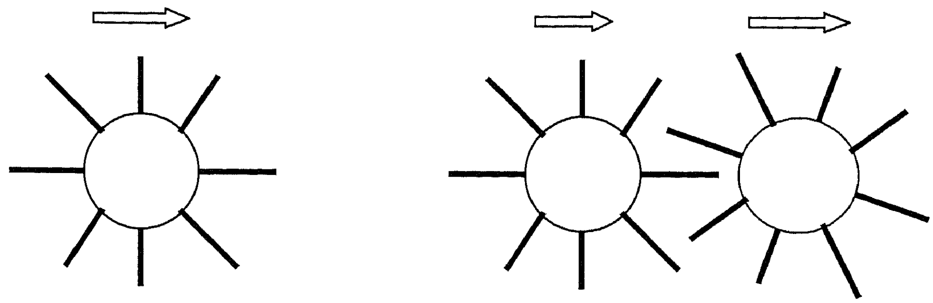

Figure 3.16 Single Rotor Dual Rotor

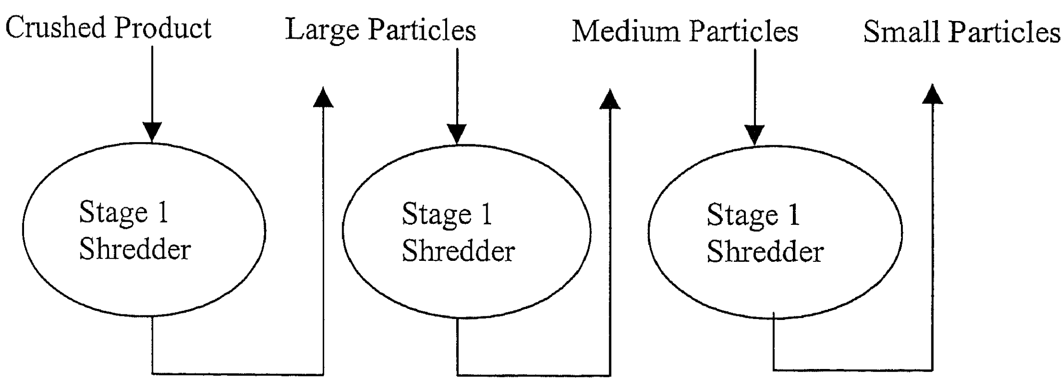

Figure 3.17 The process in a shredder

The process is suitable for a variety of products such as kitchen appliances, refrigerators, washers, dryers, automobile parts and also small appliances. The shredder output is then processes through separating facilities that are able to extract metallic particles and plastic particles.

Disassembly Force

Since a shredder uses a shearing action to cut the parts, the required shearing force will determine the force requirements. In general the shearing force can be given as the product of the shear strength of the material to be cut and the cross sectional area being sheared. In order to calculate force to shear each particle (F_P), the shearing torque (T), and the shredding power (P), let

UTS = Ultimate Tensile Strength of the material to be shred

T = average particle thickness

W = average particle width

M = maximum number of particles being sheared at any instant

R = radius of the shredder blades

N = RPM of the shredder rotor

Then,

$$F_P = 0.7\ (UTS)\ (T)\ W$$

$$T = F_P\ (M)\ R/2$$

$$P = \pi\ (N)\ F_P\ (M)\ R$$

Note that M is dependent on the material input rate, the cross-section of the shredder contact area, and the density of the input material. The shredder power is the power of the motors used to drive the shredder rotors. The power requirements tend to increase exponentially as throughput particle density increases.

Since the input material is often non-homogenous, the above equations have to be used with caution. From past experience it is understood that there is a minimum horsepower that is required to reliable and efficiently process the solid waste within a reasonable time and with a minimum of trouble and delay. The data in the following table suggest the minimum shredder horsepower for each waste category. These data are based on the existing industrial shredding practice.

Category of Waste	*Minimum Power*
Medium	200 HP
Bulky	500 HP
Heavy	1000 HP
Automobiles	1500 HP

The medium category includes paper, cardboard, bottles, cans, garbage, lawn trimmings, small appliances, small furniture, bicycles, tree trimmings, and auto tires. The bulky category includes oversize and bulky items of the above plus stoves, refrigerators, washers, dryers, doors, large furniture, springs, truck tires. The heavy category includes large and dense materials such as logs, automobile parts, and demolition rubble.

Process Variables

The main important variable in the shredder selection and in the entire process is the output particle size. The output particle size is in turn dependent on the input feed rate, input composition, and number of hammers within the shredder. As the feed rate is changed the output is changed and the work done by he hammers also changes.

3.6.2 Process Examples

Shredding process is used in most of the disassembly facilities to recover the materials at the end of the disassembly from the fluff. The fluff, which is basically a mixture of plastic and metals, is shredded so that the plastic is eliminated and the metals can be removed or extracted for further usage. For example at IBM, large quantities of fluff generated is sent to a shredder to make into smaller pieces and the plastic is eliminated from them to get the valuable materials.

3.6.3 Process Tools

There are generally 11 types of shredders used but out of them hammer mills (both horizontal and vertical) and vertical shaft grinders are used most commonly. The remaining are shears, chippers, Rasp mills etc.

3.6.4 Industry Practice

Shredding operations are used to reduce commodities to smaller and easier to handle sizes. Shredding allows more commodities to be shipped out. Other than these two operations, disassembly shops would not have shedders since they are specialized in separation of commodity from products. Scrap dealers are more interested in separation of commodity from commodity. Shredders are used more in scrap yards than in disassembly shops. Shredding along with Crushing operations are also performed on prototypes, which are basically used for testing the performance and evaluating future potential markets as in the case of auto manufacturers.

3.7 Smelting

3.7.1 Process Mechanics

Smelting is the process of recovery of any metal by melting the original input by adding some Sulfur compound. The input melts as heat is supplied to it and the required metal comes out as a sulfur compound and afterwards some other chemical reactions are performed on the compound to eliminate sulfur.

The main purpose of Smelting is to recover metals by melting the input. In the disassembly of any product if we are not able to separate the component for reuse then the aim is to recover the material and Smelting is one of the processes of recovery of the material. In this process we supply the material as input from one side to the furnace adding the sulfur compound to it and the heat is supplied from the bottom of the furnace and the material starts melting at its melting point and comes out as one of the sulfur compound with the metal or material required as the main component. After that the necessary chemicals are added to separate the sulfur to recover the metal desired.

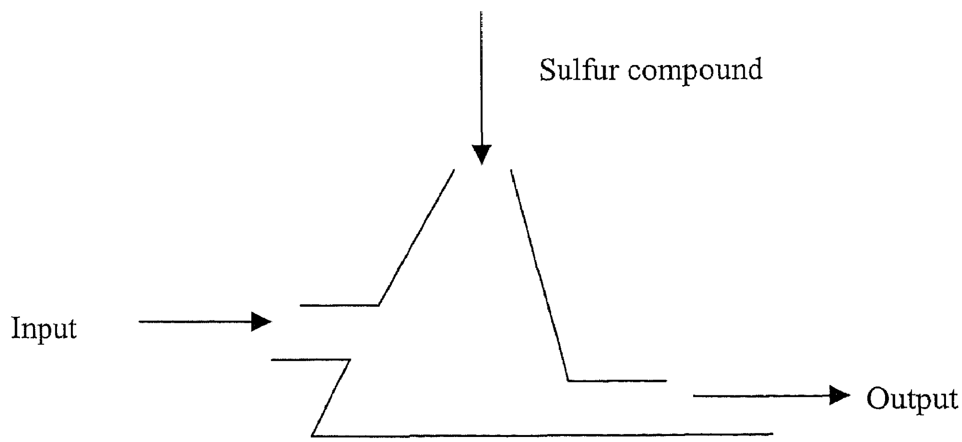

Figure 3.18 Smelting Process

Disassembly Force/Technique

We don't apply any external force for the operation. The heat is supplied to the furnace from the bottom and the metal melts after attaining its melting temperature reacting with the sulphur compound added to it before melting. After getting the output some other chemicals which react with sulphur are added to remove the sulphur present in the metal required as some compound of the metal desired. The time of disassembly or recovery depends on the reactivity rate of chemicals added to remove the sulphur and the rate of heat supplied.

Process Variables

Process variables are the variables, which are to be considered before starting the process. The important variables in this operation are the reactivity rate between the chemicals and the sulphur compound of the metal and the rate of heat supply. The reactivity rate depends on the selection of the chemical as some chemicals react at a faster rate and the other at a faster rate. If the heat supplied is at a faster then the rate of recovery is faster than if it is slow.

3.7.2 Process Examples

In the present industry smelting is still under investigation and hence it is not a widely used process when disassembly is considered. But this process becomes very useful to separate the individual metals when there is a large amount of mixture of metals.

3.7.3 Process Tools

There are no separate tools required for this process except the smelting furnace.

3.7.4 Industry Practice

As discussed earlier that this process is not in wide use at the present moment, this process is in high usage at the scrap dealers than with the demanufacturers. As large amounts of scrap is sent to different vendors Smelting is used to separate the metals from the scrap. In an automobile industry the entire metal scrap is sent to a smelting factory to recover the metals as most of the automobile body is made up of steel and iron.

CHAPTER 4

DISASSEMBLY EFFORT METRICS

Each and every disassembly step generally involves one of the two processes namely Unfastening and Disassembly. Unfastening is a process where a fastening device is removed which in effect reverses the original assembly fastening action. Disassembly is a process in which all other activities that facilitates the separation of the product into its parts. An example of disassembly action would be Shearing or Adhesive separation. At some stages if a part is by itself or if a subassembly consists of parts which satisfy material compatibility, disposal can also be thought of as an independent process. Every step in the disassembly process is evaluated independently. The approach here requires that either all possible steps are known, or a specific disassembly plan is available. This thesis focuses on the following disassembly process

- Adhesive Separation
- Chemical Dissolution
- Crushing
- Cutting
- Shearing
- Shredding
- Smelting

Presently, the industry is in search of a tool, which will help in calculating the net return on investment, quickly and easily. The facilities are unable to predict up front the likely disassembly cost. Consequently, only products on which there is high a likelihood that the return on investment would be attractive are disassembled and a point to be noted is that the part by part analysis cannot be performed using these facilities. The reason being that the disassembly usually results in a few whole parts, plus several subassemblies of similar materials, and a mixed waste stream. Therefore the focus here is on each step instead of every part.

It was found that the disassembly effort and cost was a function of several factors, much like an assembly process. Using activity based costing approach, it was concluded that seven weighted factors were needed to generate a reliable estimate of the disassembly effort and cost. The weighting for each factor is fixed and the industrial data indicate that they would be valid in most of the cases. These seven factors are known as metrics for a disassembly process. Quantification of each metric requires the development of a dual scale. One scale to measure the effort level for each factor, and one to correlate it to a common weighted scale. The relationship between the two scales is non-linear. Every step in the disassembly plan is evaluated for all the seven factors. The metrics and their associated scales are described below.

Time

The disassembly time for each step is the time it takes from the start of an operation till the end of it. This includes setup time, handling time along with the actual hands on disassembly time. The time for each step ranges between 5 seconds to a value greater than 210 seconds. Since most of the disassembly activities are manual, the disassembly time is a direct measure of the associated labor cost and hence the profitability. Total disassembly time is the sum of the times for all steps. It is natural that in most of the facilities, management projects the total disassembly time and if it exceeds the projected time the activity will not be profitable and hence disassembly is not pursued. As the projected disassembly time increases, the number of disassembly steps also increase. As a result, the average disassembly time per step tends to be the same across products. This is estimated to be between 15 to 20 seconds, while the ideal time is about 10 seconds. Further, operation times in excess of 210 seconds are rare, and tend to be bottlenecks when they do exist. Time has the greatest weighing (25%) in the proposed scale, since it is the primary direct cost element. The figure 4.1 shows the scoring card.

Tools

Tools include all equipment plus any associated handling devices needed to execute the disassembly action. As disassembly facilities handle a variety of products, it is necessary to have a wide variety of tools that assist in disassembly operation. Thus, as the tooling requirements become more specialized the capital costs tend to increase. It is observed that disassemblers would simply avoid disassembly if an uncommon tool was required, or use a destructive process to achieve the same result. The air gun, hammer, and hand saw were the three most common tools used by the disassemblers.

The tools that assist in disassembly are broadly classified in to the following categories.

- None or No tools- essentially means that the disassembly can be done with hands or at times the part itself falls out and there is no necessity of usage of any tools. This is commonly used to remove the parts, which are independent.

TIME	>240	140	90	50	25	<5	Score
	25	20	15	10	5	0	
TOOLS	Unavailable	Special	OEM	Mechanic	Air Gun	None	Score
	10	8	6	4	2	0	
FIXTURE	Automation	Winch	Clamps	Two-Hands	One-Hand	None	Score
	15	12	9	6	3	0	
ACCESS	Not Visible	Dual-axis	From below	>6" deep	X/Y-axis	Z-axis	Score
	15	12	9	6	3	0	
INSTRUCT	Training	Contact OEM	Group Discuss	>30 secs	0-30 secs	None	Score
	10	8	6	4	2	0	
HAZARD	Body-suit	Air Supply	Fire Protection	Face Mask	Gloves	None	Score
	5	4	3	2	1	0	
FORCE							Score
- Human	>50lbs	35	24	15	7	2	
- Machine	>300lbs	220	160	110	75	50	
	20	16	12	8	4	0	

Figure 4.1 The Scoring Card

- Air gun- this is a commonly used hand held pneumatically driven screwdriver or wrench. A common problem in disassembly is the variety of head types and sizes used in the same product. Very few guns are equipped with universal heads.
- Mechanical tools- these are the commonly found tools like screwdrivers, wrenches, spanners and pliers.
- OEM tools- these are the tools that are originally produced by the manufacturer to assist in maintenance and serviceability.
- Special tools- are heavy duty tools such as heavy duty hammers and crushers.
- Unavailable tools - are the ones that are not available in the market and need to be specially manufactured to disassemble. Tooling costs in disassembly tend to be insignificant and hence tools have a relatively low weighing (10%) in the scale.

Fixture

Fixture is the part holding facility that assists in disassembly. Fixture is a dependent variable on time as it adds on to the set up time. The faster the set up is, the easier it is to disassemble. Fixturing requirements have been one of the primary impediments to efficient disassembly of large products.

The primary anchors in the fixture scale are described as follows.

- None- when there is no need of any fixture while disassembling.
- One hand- when only one hand is required to hold while disassembling. This is usually applicable for small products.
- Two hand- two hands are required to orient the product while disassembling.

- Clamps- are like vises that are used to hold the part. These also include grippers, bench vise and hand held vises.
- Winch- these represent powered fixtures.
- Automation- represents fixed or programmable automation equipment to grip the product. Fixturing costs are significant, as it is a reference to the time i.e. set up time and therefore have a relative moderate weighing (15%) in the scale.

Access

Represents or focuses on the way a part is accessible while disassembling. In disassembly the parts or points of interest could be anywhere in the product. The primary anchors in the access scale are described as follows.

- Z-axis- refers to the easiest access for manual disassembly.
- X/Y axis- refers to accessibility from side of the part.
- Greater than 6" deep- when the disassembly point is more than 6" deep from the product surface. This usually results in a long processing time, as the worker has to insert the entire wrist and at least half of an arm.
- From below- or a negative Z-axis - this requires a special fixture to make the access possible.
- Dual axis- when the disassembly point is accessed with the help of a flexible or bent tool.
- Not visible- when the disassembly is inside the product and not visible. Accessibility is also a key factor in disassembly costs and hence has a weighing of 15% in the scale.

Instructions

Instructions help, train, assist the disassemblers to optimize disassembly process thus reducing time and disassembly cost. A disassembly facility must process a variety of products. In order to process them the worker must be well used to them to completely the disassembly in the projected time otherwise there is no use in disassembling the product. Even if the facility is processing a single variety of products there might be lot of internal design changes, implying they may have different disassembly plans. Keeping the above issues in concern the worker must be provided with some kind of instructions, which will help him disassemble the product at the earliest.

The primary anchors in the instructions are described as follows.

- None-implying there is no need for any sort of instructions.
- 0-30 seconds and greater than 30 secs- implying the time range the user or worker is required to get himself acquainted about what to do next?
- Group discuss- if the worker needs to discuss the situation with the other or the line supervisor.
- Contact OEM- to consult the OEM documentation about how to continue with disassembly.
- Training- sometimes-special training is given to the workers so that they can know the product before hand and which may help them for quicker disassembly. Instruction is a common element in disassembly costs but is usually not significant, and hence has a relatively low weighing (10%) in the scale.

Hazard Protection

Disassembly operations are characterized by destructive activities and broken parts, coupled with an uncertain input stream. Hazard instructs and trains the operator from the dangers that occur, and to protect himself from them. In these situations the potential for wide range of worker hazards exists. Battery acids and gasoline vapors are examples from the automobile disassembly process.

The primary anchors in the hazard scale are described as follows.

- None- implying there are no known hazards and hence there is no need of any protection while disassembling.
- Gloves- to escape from the hazards the hands may encounter like sharp edges and also from chemical acids.
- Face masks - facemasks are needed when unbreathable particles become airborne and mostly occur during cutting or grinding operations.
- Fire protection- needed when explosive materials are being handled. As an example, in the disassembly of automobile airbags.
- Air supply- when the ambient atmosphere must be cleaned using a special purpose ventilation equipment.
- Body suit- when the worker must be fully covered with no skin exposure. Hazard protection has a relatively low weighing (5%) in the scale.

Force Requirements

Force is a direct reaction of the disassembly effort per component, per part, per fastener. Disassembly is inherently a forceful activity, whether one is doing a simple unscrewing activity or a hammering activity, a force must be exerted. The force requirements can be usually met either by human or by a machine. At any point of disassembly evaluation either one category of force can be used but not both. Hence there are two scales here one which indicates the force applied by a human and the other by a machine. The rational for this is that the same force intensity has different degrees of intensity depending on how it is applied.

The human and machine scales for force requirements are quite straightforward. The anchors for the human force are based on conventional ergonomics, which specify a maximum comfortable human force of about 50lbs. The anchors for the machine scale are based on the economic costs of the machinery. The range is between 50 and 300lbs. Force metric has a relative weighing of 20% in the scale.

Demanufacturing involves two specific mechanical processes. One is unfastening and the other is disassembly. Different disassembly processes are studied and came up with some metrics that assists in ease of disassembly. So disassembly effort metrics are the metrics that help ease the operation. The different metrics that are used in each of the disassembly processes are

- Time
- Tools
- Force
- Fixture
- Instruct
- Hazard and
- Access

Access is the metric generally used for unfastening operation and is very rarely used in the disassembly operation. In all the following disassembly processes accessibility gets a score of '0', as it is not considered. It should be noted that the metric 'force' may be either the force applied by human or the force applied by the machine. Depending the force requirement for the process in consideration it may be any of the above two. This section of the thesis discusses the use of the above listed metrics with respect to different disassembly processes. For each process the mean or generally used values are examined. The scores for all the disassembly processes with all effort metrics is shown in figure 4.2. In all these processes the scores indicate the mean or mostly used values. The figure gives the details about each process with all the effort metrics and their scores. The scores for each metric is the mean value or mostly expected value for that process. All these scores explain the difficulty levels involved. The lower the score the better the process. It must be noted that all the parameters or metrics are not used in all of these process as they are not needed for the disassembly operation to take place.

Process	Time	Tools	Fixture	Access	Instruct	Hazard	Force	Score
ADHESIVE SEPARATION	22	2	2	0	2	0	0	36
CHEMICAL DISSOLUTION	20	2	2	0	1	1	0	26
CUTTING	15	6	8	0	2	1	8	40
CRUSHING	22	6	2	0	1	2	12	45
SHEARING	22	6	8	0	2	2	12	52
SHREDDING	20	6	2	0	2	2	16	48
SMELTING	20	2	2	0	2	1	0	27

Figure 4.2 The Scoring Card for Disassembly Processes

The mean score for Adhesive Separation process is 36. In this process the force applied is only human force as lesser forces are enough to peel the adhesive with a knife and most of the time organic solvents are used to remove the adhesives. It is also clear that the tools required for this process ranges between None to Mechanic. In this process one must be careful while applying the organic solvents, as they may be hazardous to the user if it falls on the hands. It should be also noted that the removal of adhesives by the application of organic solvents or chemical reagents will take a longer time and hence the process of removal is slow.

In Chemical Dissolution process the rate of removal of the material depends on the rate of reactivity between the etchant and the material to be removed and for this reason the time required is supposed to be high and hence the process is slower. In this operation also the tools required range between none mechanic as the tools required are for only the surface preparation where the etchant is going to be applied for material removal. In this operation the metric 'force' is not at all considered, as there is no application of force in the process. The mean score for this process is 26.

Cutting is the widely used operation in the present demanufacturing industry. For example cutting operation is used in the disassembly of automobiles to create the accessibility to the engine by removing the rubber hoses and also removing the damaged areas in the automobile body. The time taken for disassembly is calculated by using

$$T = L/Vf$$

Where T = time in seconds

L = length of cut

Vf = Feed rate

The range of tools necessary for this operation are varied and hence there is a need for special tools also. In this operation the application of force is the force applied by machine, as higher forces are required to cut apart. The mean score for this process is 40.

Crushing process is presently used to crush the fluff or solid waste at the vendor site and at times it is used to get valuable materials from the prototype models. The time required for this operation depends on the throughput size required at the end of operation and the time the figure indicates is the mostly used range for the different throughputs that are in practice in today's industry. In this operation also the force applied is the force applied by machine but not by human. The output coming from the crusher may cause hazard to the operator and hence a facemask is required to avoid the hazard. The mean score for the operation is 45.

Shearing is also one form of cutting and hence is also widely used in today's demanufacturing industry. The force applied is through machines and not by humans and the force required is given by the product of the area of cross section of the material to be cut and the shear strength of the material, which is to be sheared. As the shear strength of a material remains constant the force is directly related to the area of cross section to be sheared. The mean score for the process is 52.

In Shredding process the important parameter is the throughput size which changes depending on the physical constitution of the input and the feed rate and this determines the amount of time required for disassembly by this process. As the shredder uses a shearing action to cut the parts, the required shearing force will determine the force requirements. This process is mostly used to recover the materials at the end of disassembly from the fluff. Facemask is necessary to get rid of any damage or danger that may cause because of the output-shredded particles. The mean score for the process is 47.

Smelting process is used to recover metals by melting the input and this operation takes place in a furnace. There is no need for applying any external force for this operation as the heat supplied to the furnace melts the metal to be recovered. Hence there is no need to consider the force metric in this process. The time of disassembly or recovery depends on the reactivity rate of chemicals added and the rate of heat supplied. The mean score for this process is 27.

Case Study of DeskJet Printer

The following case study of DeskJet computer printer clearly depicts the use of the disassembly scoring card or the disassembly scales. DeskJet printer has a optimum life-span of 3 to 4 years and is disposed off in relatively large quantities. In the direct disposal route the entire product would be sent to landfill "as is". A nine-step disassembly plan for this product was formulated. The plan and the associated DEI calculation are shown in table 5.2. Note that other disassembly plans are possible, and could potentially be better than this one. Table 5.3 lists the parts or components that are separated from the main assembly along with their material composition. All the plastic pieces are of the same type and would be sent to a plastic recycler, while the circuit board would be sent to a precious metal recycler. The power unit is a reusable asset, and in current markets it is auctioned in bundles. The steel pieces would be sent to a ferrous metal recycler, while the mixed waste would be sent to landfill.

Table 4.1 The Disassembly plan and DEI worksheet for the DeskJet Printer

Step #	Description	Time	Tools	Fixture	Access	Instruct	Hazard	Force	Total	Time(sec)
1	Release snaps and pull out front tray assembly	1	0	3	3	0	0	4	11	8
2	Use chisel level to remove side carriage cover	0	4	3	3	0	0	0	10	5
3	Unscrew and remove top fasteners (X2)	0	2	0	0	0	0	4	6	4
4	Release bottom snaps and remove printer upper housing	3	4	6	5	2	0	3	23	10
5	Release latches and remove printer cartridge (X2) from cradle	0	0	0	0	0	1	0	1	5
6	Unscrew (X3) and remove power supply and connection unit	3	2	3	4	1	0	4	17	10
7	Using scissors cut out ribbon write to cartridge cradle	0	3	0	0	0	0	0	3	2
8	Unscrew (X2) and then use lever to remove circuit board	4	3	6	3	1	1	4	22	20
9	Use lever to break bottom printer housing from carriage assembly	1	3	3	0	0	0	4	11	8

The two key measures generated from the analysis are the DEI score of 104 and the total disassembly time of 72 seconds. Step 8 takes the longest time because of the difficult levering action, while step 4 has the highest score because of fixturing needs and the associated accessibility. Step 4 is not necessarily bad, since a large mass is released. Steps, which have high score and Low Mass releases, are usually least cost effective. The above table must be used by the product team to focus on difficult steps and hence improve the disassembly effort.

Table 4.2 Pieces Generated in Printer Disassembly

Piece #	*Description*	*Material*
1	Front tray subassembly	Plastic
2	Side cover	Plastic
3	Screw fasteners (x7)	Steel
4	Printer upper housing subassembly	Plastic
5	Power supply and connection unit	Reuse Asset
6	Ribbon wire	Mixed Waste
7	Printer Cartridges	Mixed Waste
8	Printed circuit board	Electronic
9	Carriage subassembly	Steel/Plastic
10	Printer bottom housing	Plastic

In general the printer has a good design from a disassembly perspective. Potentially all the pieces, except #6 and #7, can be recycled or reused.

CHAPTER 5

SOFTWARE DEVELOPMENT

5.1 Introduction

In today's industry there are no common tools available for disassembly and every industry has its own tool suitable for their process and these are mostly manual. There is no generic tool available for disassembly, as those are available for assembly. This issue is the main concern in developing some tools, which will ease disassembly. Presently the tools that are available include disassembly evaluation charts, disassembly time estimates, checklists and some design standards or guides. But these tools will not help to quantify the disassembly operation and there is a growing need for such tools that would justify the investment for disassembly operations.

The above issues gave rise to the development of computer based tools that would help to quantify the operation. Most of the computer based tools just talk about generating a disassembly sequence for ease of disassembly but they do not generate any process plan. It is equally important to check whether the tool performs environmental product assessment. Generally environmental assessment involves verification with an established environmental checklist to see whether the product or component satisfies the required conditions. So it is important to develop a tool that will generate the disassembly sequence time and cost prediction or the return investment to evaluate whether the disassembly operation can be carried out within defined time and cost constraints. Some of the computer-based tools that are presently in the market are ReStar, ECO-Fusion, Ametide, DFR-Recy, EUROMAT.

5.2 Disassembly Effort Index Calculator

Disassembly Effort Index (DEI) Calculator is a computer based tool, which visualizes disassembly as a multi-step process or plan. As stated earlier one of the aims of this thesis is to develop a software that quantifies the disassembly operation. DEI Calculator estimates the amount of return one is going to get from disassembly either from recycling or reusing the different materials or components and disposing the hazardous materials in a safe manner. In a multi-step process plan, at each step one or more parts with certain commonalties are separated or removed. The figure 5.1 depicts an analytical process for developing a product disassembly and disposal plan which shows the flow of operation in DEI Calculator. The inputs are supplied to DEI in the form of Bill of Materials, which include the material composition, part reusability and also any known hazards, the parts or components present in the bill of materials may cause. Once the bill of materials is supplied to the system it is necessary to tell how the parts or components connected to each other. The DEI Calculator utilizes the above mating structure and gives the details of various subassemblies formed at each step of a process plan until the end of disassembly operation.

Once the mating tree is formed then the DEI tool is ready to generate a process plan which indicates the actual disassembly sequence. The Process plan may be either a descriptive one or a prescriptive one. In a descriptive plan the user performs the disassembly operations as he wishes but in a prescriptive plan the system gives suggestions depending on the hazardous nature, reusability and also on material compatibility. Out of the descriptive and prescriptive plans one of the plans is optimized depending on the revenue generated at the end of disassembly operation. One never

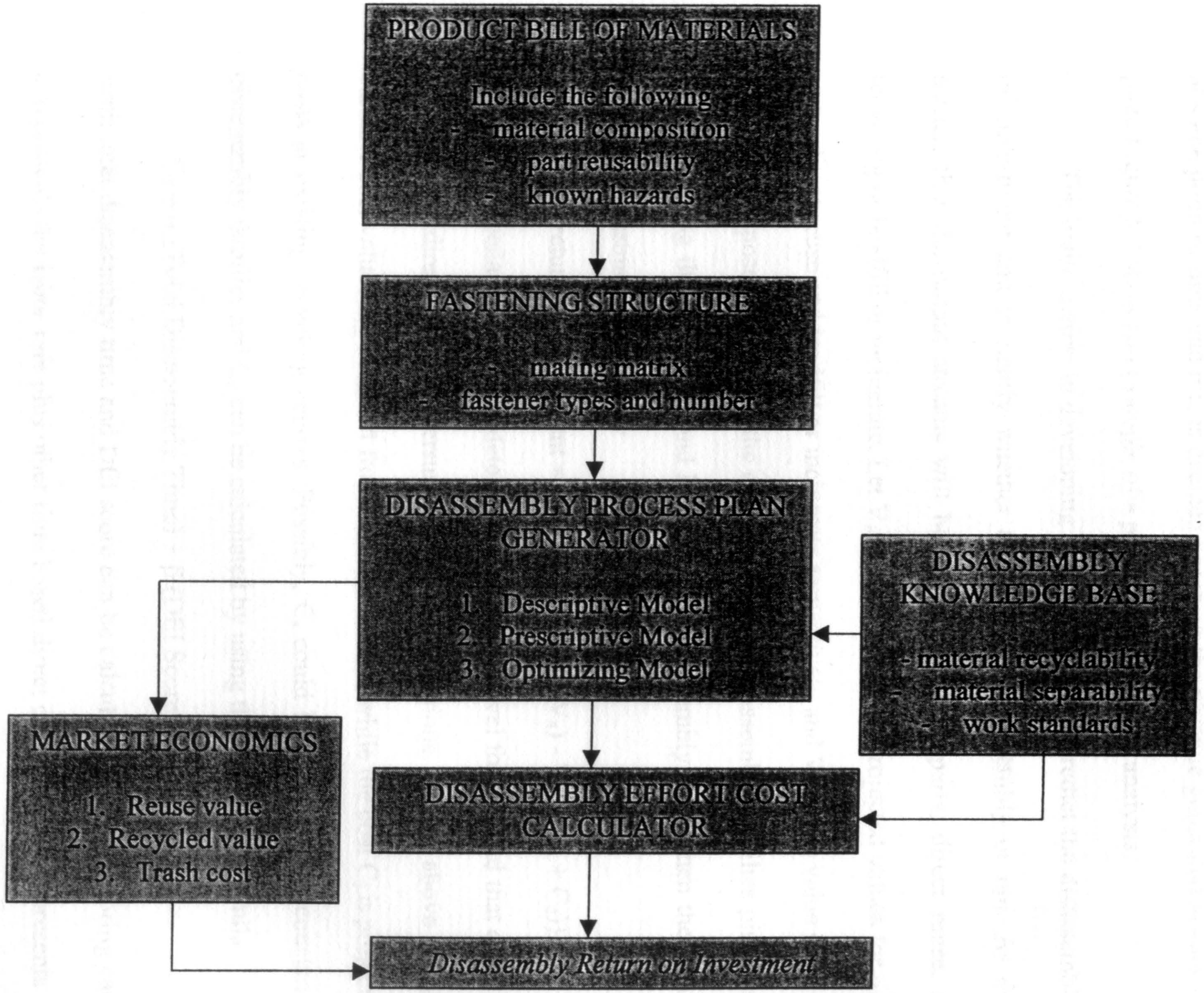

Figure 5.1 An analytical process for developing a product disassembly and disposal plan

wishes to disassemble a product completely and disassembly operation must be stopped at some point of time and this is decided based on the revenue generated at each step in a plan. Figure 5.2 shows an example of a process plan for DEI analysis.

The main interest in developing this software is to predict the disassembly return on investment and to justify whether to adopt the disassembly or not. As discussed earlier, that the output streams will be either reclaimed parts, direct reuse, material recycling or landfill or incinerate. Let V_1, V_2 and V_4 be the projected values for reclaimed parts, direct reuse and landfill or incinerate respectively and W be the value if the product is directly disposed. Let C_s be the cost to sort into disassembly families plus the logical cost of moving the inventory, and let C_d be the disassembly cost. Then the disassembly return on investment is given by

Disassembly return on investment = Rd = $\{[(V_1 + V_2 + V_4) - W] / (C_s + C_d)\} - 1$

For a given scenario one could determine a threshold level for Rd, and that could be used to make the direct disposal versus disassembly decisions. In the above equation the variable cost values are obtained from the market data, while the cost C_s is projected from costs at existing recycling centers. Possibly, C_s could be a predefined constant for all disassembly families and C_d can be calculated by using the following formula

$$C_d = \alpha \text{ (Total Disassembly Time)} + \beta \text{ (DEI Score)}$$

Both total disassembly time and DEI score can be calculated from the scoring card. Here α represents the labor rate plus other time based direct costs, while β represents the cost conversion factor. β is representative of the indirect and overhead cost and can be estimated by calibrating past cost performance of the facility with the DEI scores. For instance, if the indirect and overhead cost for five previously proceeded products can be

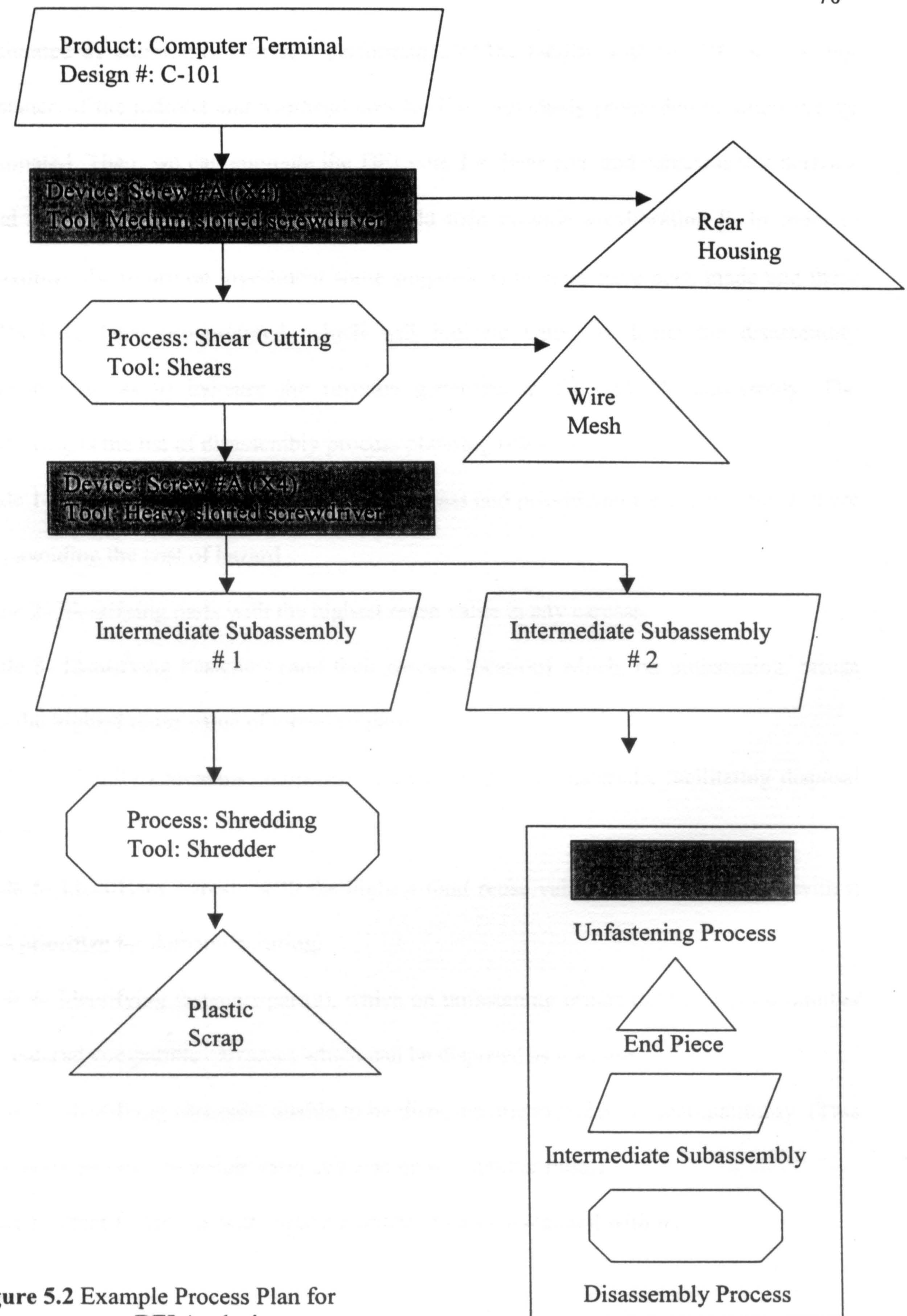

Figure 5.2 Example Process Plan for DEI Analysis

estimated by calibrating past cost performance of the facility with the DEI scores. For instance, if the indirect and overhead cost for five previously proceeded products can be estimated. Then, we can compute the DEI core for these five and subsequently derive a trial β for each. The average of these would then provide a calibrating β. In order to maximize the return on investment some suggestions or rules have been made and these rules have been programmed, which will indicate where to focus the disassembly operation so as to increase the revenue generated at the end of disassembly. The following is the list of disassembly process planning rules

Rule 1- Identifying hazardous parts in any carcass and prioritizing them for removal there by, avoiding the cost of hazard.

Rule 2- Identifying parts with the highest reuse value in any carcass.

Rule 3- Identifying Fasteners (and their carcass location) which, on unfastening, brings out the highest reuse value of retrieved parts.

Rule 4- Identify Carcasses composed of only compatible materials, facilitating disposal wholly.

Rule 5- Identifying carcass with the highest total reuse value of parts associated with it and prioritize for demanufacturing.

Rule 6- Identifying fasteners/part(s), which on unfastening brings out the highest number of material compatible carcasses which can be disposed as a whole.

Rule 7- Identifying carcasses unable to be disposed due to material incompatibility. (This rule is based both on weight ratio and also on the number ratio.)

Rule 8- Identify carcass with largest number of parts associated with it.

The manner in which DEI Calculator is used to estimate the disassembly effort is explained by going through snapshot of each screen in the software, which gives the details of disassembly of a VCR. The figure 5.3 shows the bill of materials of VCR in which the parts and fasteners are seen separately in two different tables. There are also buttons, which will help to change the details, if the details are entered incorrectly.

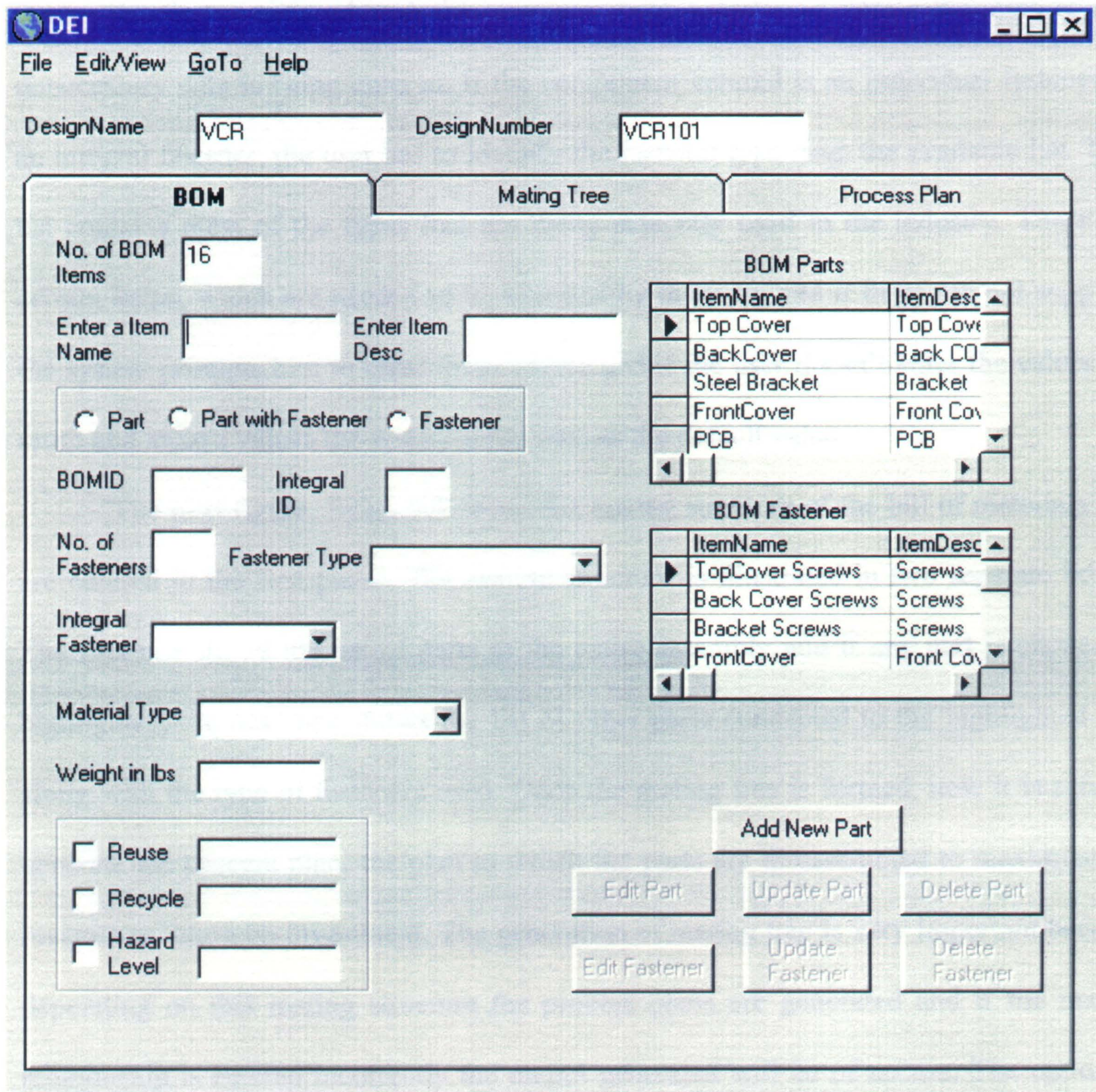

Figure 5.3 Bill of Materials Tab

The Bill of Materials tab for disassembly operations is different with respect to conventional methods as this tab contains the data or details regarding reuse value and recycle value at the end of life of a component. In this tab there are many options to identify whether the component that is being entered is a part, fastener or part with fastener like an integral fastener. There are options related to editing the components if wrong details are entered and the user can even remove or delete the data if any unnecessary data is being entered. If the component entered is an individual fastener or an integral fastener, the user has to identify the fastener type from the available list. This list contains most of the types that are being presently used in the industry. There are certain items, which are needed to be supplied by the user, and if these are not supplied the system prompts him to enter those values and if the user doesn't enter the values for reuse and hazard values the system takes zero as the default value.

The next figure, figure 5.4 shows the mating structure of the bill of materials that are entered in the first phase. The mating structure is illustrated in two separate boxes. The first one shows the list of parts in the entire assembly and if any part is clicked or highlighted, the next box shows the list of other parts connected to the highlighted one along with the type of fasteners used. Once the mating tree is formed, now it is time to generate the process plan, the plan in which the parts are disassembled to maximize the revenue or return on investment. The generation of mating tree is very important because depending on this mating structure the process plans are generated and if the mating relationship is entered incorrectly the output generated will be of no use. The option of selecting the kind of fastener that binds various parts is provided and depending on the option the user is provided with a list of fasteners available from the list entered in bill of materials.

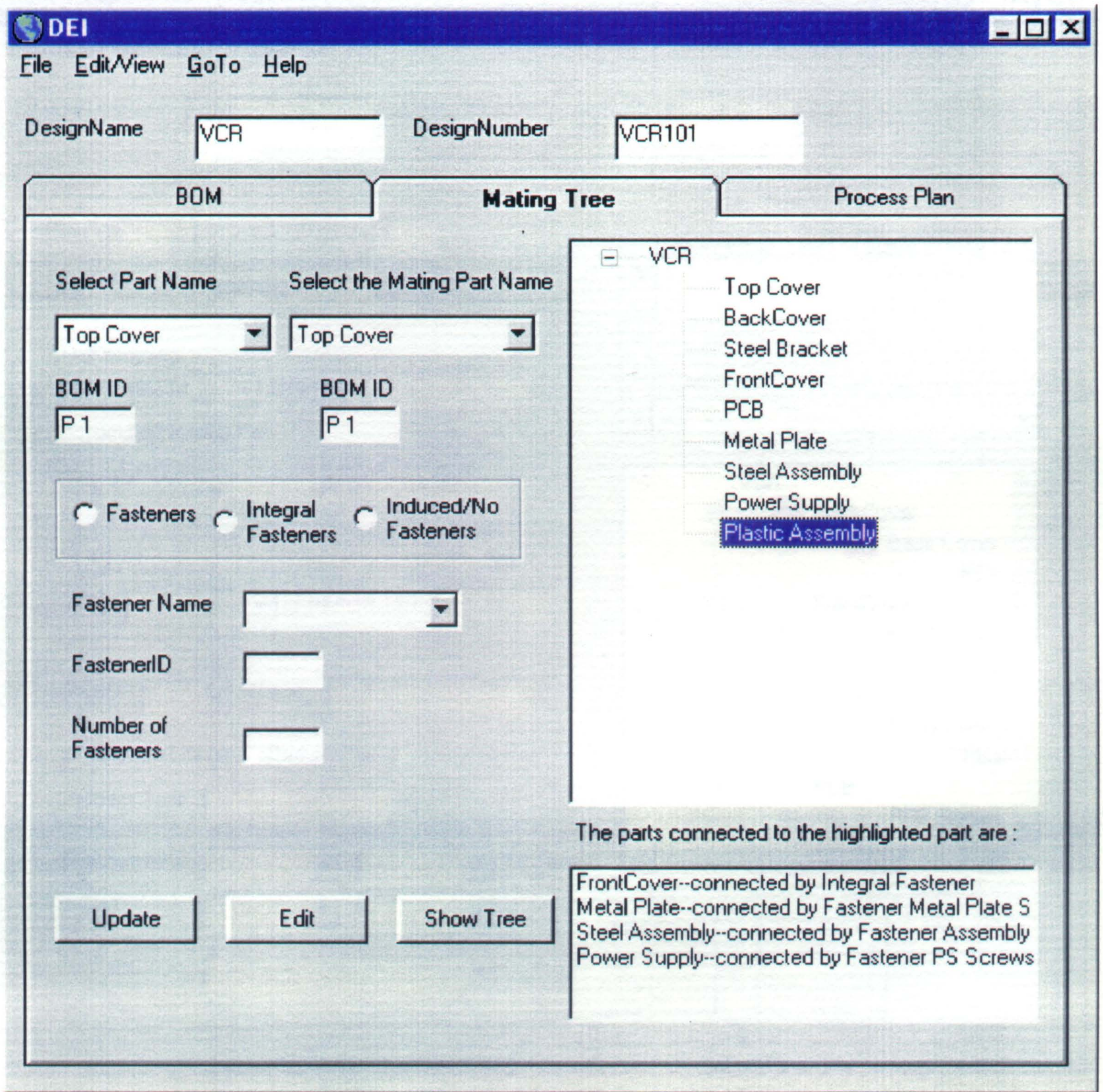

Figure 5.4 Mating tree

Hence the mating relationships forms an important part in this software and the user has to take proper care before continuing with other steps.

The next Process Plan tab is supposed to be the heart of the software as the entire process plan is being generated here. The following figure 5.5 shows the process plan tab.

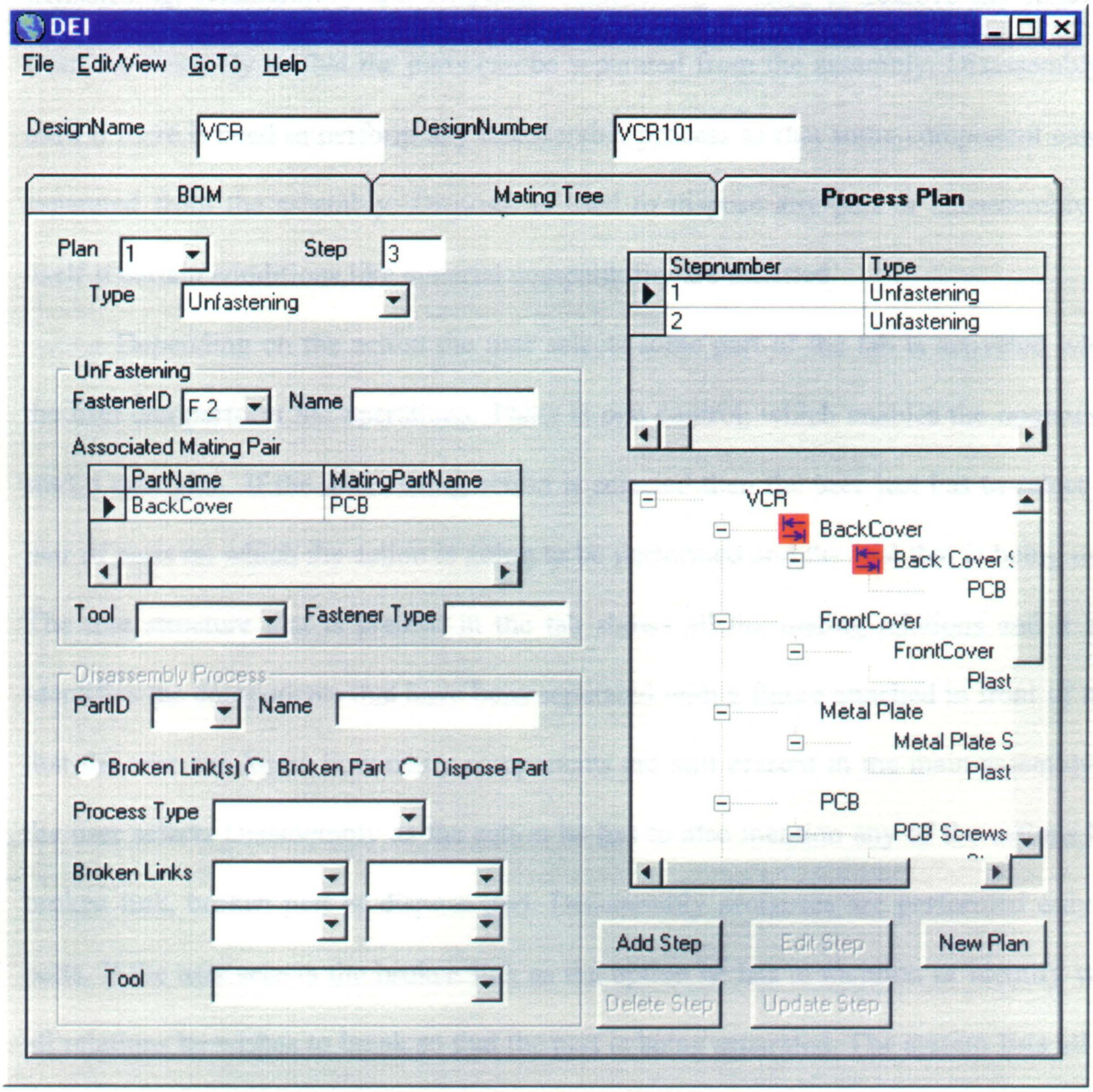

Figure 5.5 Process Plan Tab

For a single product there may be any number of plans and this is the reason the tab contains a separate list for plans and steps. The system generates some suggestions indicating where to concentrate so that the parts with higher reuse values are separated quickly from the main assembly and also to eliminate the hazardous parts so that the negative value on the total return can be eliminated. There are three different actions from which the user can select to perform some operation. The three actions are Unfastening, Disassembly and Disposal. Unfastening is used to remove the fasteners from the assembly so that the parts can be separated from the assembly. Disassembly is used if there is need to perform any disassembly process so that some component can be separated from the assembly. Disposal is used to dispose any part or subassembly by itself if certain conditions like material compatibility are satisfied.

Depending on the action the user selects some part of the tab is activated where the user can perform the operations. There is one control, which enables the operator to start a new plan. If the unfastening action is selected then the user just has to select the pair of parts on which the action is going to be performed and the tool that is being used. The tree structure that is present in the tab shows all the mating relations and it also identifies the components that have been separated with a figure attached in front of it so that the user can know how many components are still present in the main assembly. If the user selects Disassembly as the action he has to also mention any of the actions like broken link, broken part or dispose part. Disassembly processes are performed only on parts. If the user selects the broken link as the option he has to mention or identify what all relations he wishes to break so that the part is being separated. The system lists all the relations that exist with respect to the part that is being disassembled. If broken part is chosen as the option then the part is not separated from the main assembly but the part is made into as many number of pieces as the number of the relations the part holds and each piece goes with one part. For example if two parts are connected by a rubber hose then the rubber hose can be broken into two parts so that one half is with two parts. Some operations results in individual parts, which can be removed or separated from the main assembly without further performing any other operations. For such parts the dispose part option can be selected.

Like the bill of materials tab the user can edit the steps that are performed or even deleted some steps which he thinks are not necessary. Depending on the type of action selected and also the type of process the disassembly effort can be calculated by using the scoring card discussed earlier for each process which lists the difficulty level with respect to each metric and also the total time taken which can be used to calculate the disassembly return on investment.

CHAPTER 6

CONCLUSIONS & RECOMMENDATIONS

The importance of the disassembly problem is recognized by most industrially developed countries, with different emphasis on the issues concerning legislation, standardization, basic research and industrial implementation. Nevertheless, it is easy to foresee that only a development of disassembly technology (now still in its infancy) can give a decisive impulse to the development of easy-to-recycle products and to computer based design disassembly processes and systems. While the initial industrial experiences are widening the knowledge of the different facets of the disassembly problem, an increasing attention to research on product, process and system design can be expected. Future developments will depend on legislation that is going to set up the constraints for recycling. To meet the requirements of the expected regulations, enterprises should start to take responsibility for recycling their products themselves or making them available for the recycling process [6]. This chapter summarizes the importance of disassembly problem and the techniques that can be used for taking care of the existing worn out products and also some design guidelines for producing the products which are easy to disassemble.

It is concluded that the disassembly process many not be completely standardized and automated. The main reason for this is the complexity involved in the process and the decision of the demanufacturer regarding the end-of-life scenarios of the recovered material. From the disassembly diagram one gets the information about the disassembly sequence of any product but it is concluded that there are operations in the disassembly process that can be done simultaneously. Hence the product must be designed in such a manner that there is minimum dependency between components. This ensures more simultaneous disassembly operations and this reduces the disassembly time and effort and hence sequence dependency and independency play a important role in the disassembly process.

The scoring model provides an effective and efficient tool for estimating the disassembly effort and cost. These costs provide valuable inputs to a variety of disassembly economic models. This cost analysis indicates that the level of disassembly, the time required for the individual disassembly operations within the entire assembly and consequently for the complete product and the end of life options for the recovered materials are interrelated. For economic and profitable operation of the demanufacturing industry, a trade off between these factors is essential. Increasing the level of disassembly to recover purer materials requires more time and increases the labor cost associated with it. On the other hand, reducing the time by recovering fewer amounts of purer, high valued materials, does not give enough pay back for demanufacturing to be economically viable. So, it can be concluded that the demanufacturer should decide the end of life options before the disassembly operation starts and accordingly adopt a disassembly process. The DEI model requires the user to first have a disassembly plan, and second the ability to reliably select the corresponding scale values in the scoring card. These effort and cost estimates can be used to

1. Make direct disposal versus disassembly decisions
2. Make a bid for the purchase of disposed products
3. Levy disposal fees on consumers and

4. Improve the disassembly costs at the design stage.

The study of disassembly is just not related to or concentrated only on worn out products but the difficulties involved in the disassembly of existing worn out products must be studied carefully and keeping those in view the design of the new products must be changed so that the same difficulties will not be seen. The following is a list of guidelines developed at Manchester Metropolitan University in the area of product design keeping the disassembly problems in consideration. The guidelines are divided into three areas namely, materials, fasteners and connections and product structure. The following tables list the guidelines in the above three areas [a]

Table 6.1 List of Guidelines

Materials	**Reason for Guideline**
Minimize the number of different types of material	Simplify the recycling process.
Make subassemblies and inseparably connected parts from the same or a compatible material	Reduce the need for disassembly and sorting.
Mark all plastic and similar parts for ease of identification	Many materials value is increase by accurate identification and sorting.
Use materials which can be recycled	Minimize waste; Increase the end of life value of the product
Use recycled materials	Stimulate the market for recyclates.

Table 6.1 (Continued)

Ensure compatibility of ink where printing is required on plastic parts	Maintain maximum value of recovered material
Hazardous parts should be easily removed	Rapidly eliminate negative value
Eliminate incompatible labels on plastics	Avoid costly label removal operations

Fasteners & Connections	
Minimize the number of fasteners	Most disassembly time is fastener removal
Minimize the number of fastener removal tools needed	Tool changing costs time
Fasteners should be easy to remove	Save time in disassembly
Fastening time should be easy to access	Awkward movements slow down manual disassembly
Snap-fits should be able to disassembled using standard tools	Special tools may not be identified or available
Try to use fasteners of material compatible with the parts connected	Enables disassembly operations to be avoided
Make incompatible parts easy to remove	
Eliminate adhesives unless compatible with both parts joined	Many adhesives cause contamination of materials
Minimize the number and length of interconnecting wires and cables used	Flexible elements slow to remove; copper contaminates steel, etc

Table 6.1 (Continued)

Connections can be designed to break as an alternative to removing fasteners	Fracture is a fast disassembly operations
Product Structure	
Minimize the number of parts	Reduce disassembly time
Make designs as modular as possible, with separation of functions	Allow options of service, upgrade or recycle
Locate unrecyclable parts in one area which can be quickly discarded	Speeds disassembly
Locate parts with the highest value in easily accessible places	Enables partial disassembly for optimum return
Design parts for stability during disassembly	Manual disassembly is faster with a firm working
Avoid moulded metal inserts or reinforcements in plastic parts	Creates the need for shredding and separation
Access and break points should be made obvious	Logical structure speeds disassembly and training.

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