ABSTRACT

CASE STUDIES IN DISASSEMBLY PROCESS PLANNING

by
Riteshkumar Dhimmar

The rapid advancement in technology started in last century and still continuing resulted in decreased life cycle of electronic products. It also resulted in increased product disposal rate and filling land fill space faster causing shortage of such space and consequently creates major environmental problems. So, since couple of decade environmental concern has focused on production process and environmental regulations imposed by government has watched industrial pollution. With government regulations to control environmental problems; consumers are also aware of adverse effects of product disposal forcing manufacturer to become more responsible for safe product disposal and recycling of used product.

A necessary condition to disassemble any product more efficiently is the availability of a disassembly process plan. In this thesis we represent set of intelligent disassembly rules that are able to automatically generate a disassembly plan. Few electronic equipments have been used to carry out experiments of disassembly process plans generation. So, based on established disassembly rules disassembly process plans have been generated having several steps in each plan. Each step describes action to be taken on particular part of assembly, disassembly time and effort we need to put to carry out that operation. Final economic analysis is carried out to show economic gain achieved though disassembly process.

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This Thesis is dedicated to my parents and my family
for their constant inspiration

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CHAPTER 1

INTRODUCTION

1.1 Disassembly Concept

The obvious fact of today's world is electronic equipments have shorter life cycle compare to other consumer products. Reason of this fact is the increased customer appetite for new facilities or range of products resulting in emerging of new technologies and rapid product development, market is gets filled by so many new products everyday. As new products are coming to the market, old products are being disposed. So, with the increase of product development rate, product disposal rate is also increased. At the disposal rate of products has achieved that much level that environment concerns has been shown up on the surface. Resource optimization (energy and material) and environmental issues in product life-cycle context are taken very seriously by companies as well as government agencies [11]. These led to development of the rules and regulations laid by Environmental Protection Agency (EPA), disposal of hazardous materials/waste, limited landfill space, the resulting scarcity of natural resource and raw materials [12].

It was common practice that a few parts from a product were recovered and remaining product was disposed. So, lack of efficient disassembly process, product was not fully recovered and resulting in limited landfill space. Both the lack of natural resource, raw materials and energy, and the shortage of landfill or water burning capacities force the industry to consider ways to increase the amount of components and materials that can be reused for a "second life" [2]. To get the parts for "second life" product has to be disassembled.

Disassembly applications deals with numerous kinds of industries as discrete parts and products are part of almost all kinds of industries. Almost all the companies are trying to implement disassembly centers similar to that of a manufacturing division where by trying to reuse and recycle the used products and hence 'Closing the Loop' of materials and components [9]. This is the main reason why most of the companies are adopting disassembly process as much needed process at their facility to get their materials back for further use. By applying efficient disassembly strategy, company can get more values by reusing recycled materials compare to actual disassembly cost of product.

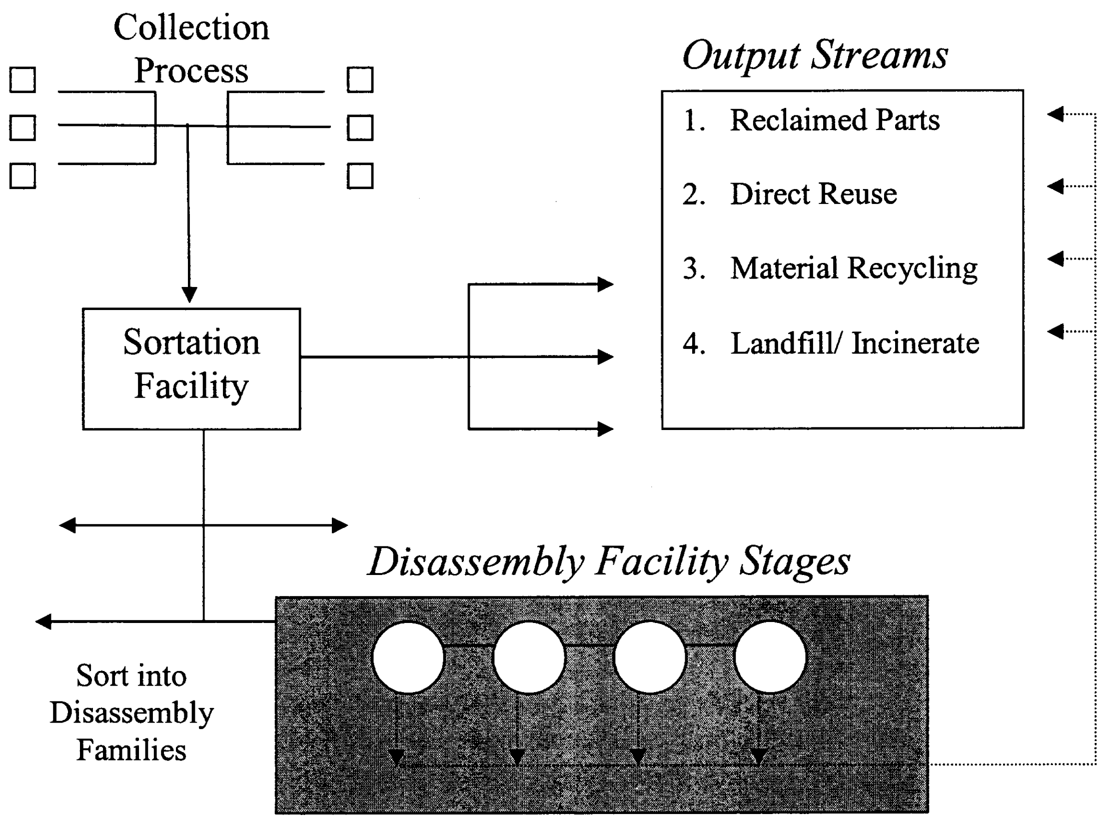


Figure 1.1 Disposal and disassembly process [7].

Reclamation of parts for recycling or reusing by disassembly process was not seriously considered while designing the products till recent years. That implies that advantages or disassembly process was not well understood by product manufacturers and that kept disassembly process as labor intensive. Automation in disassembly process is still not achieved at such level where one can assess disassembly as profitable process as it can help in getting value from reusing of recyclable parts. So, at the end of life of product, disassembly will be still expensive and labor intensive process, unless disassembly guidelines are taken into consideration during the design stage of product.

1.2 The Disassembly Process

Disassembly defined as the process of systematic removal of desirable constitute parts from and assembly while ensuring that there is no impairment of the parts due to the process [10]. Disassembly process output depends on product structure and according to it; disassembly process can be called as complete or partial disassembly. Disassembly process plan is a documentation of steps to be carried out to disassembly certain product from its original shape to the tiny parts achieved through it which are the prime interest of part to be disassembled. Disassembly process planning is a relatively new subject, and has only recent received attention in the research literature compare to assembly process planning, which is a highly developed subject and several well known methods are widely used in industry [4].

Design for disassembly is new approach which can significantly improve the ease of separating material for recycling. Disassembly process is further divided in disassembly sequence planning, disassembly process planning and disassembly evaluation. Disassembly sequence planning is process of identifying order in which product is to be disassembled. Disassembly evaluation is basically product evaluation before starting of disassembly process for its end profit and estimated time. Product is closely evaluated before actually disassembly process is carried out and particular parts and subassemblies are located to be recovered. To identify such parts and subassemblies some criteria are decided. The criteria that can be used before starting of disassembly process are shown in figure below.

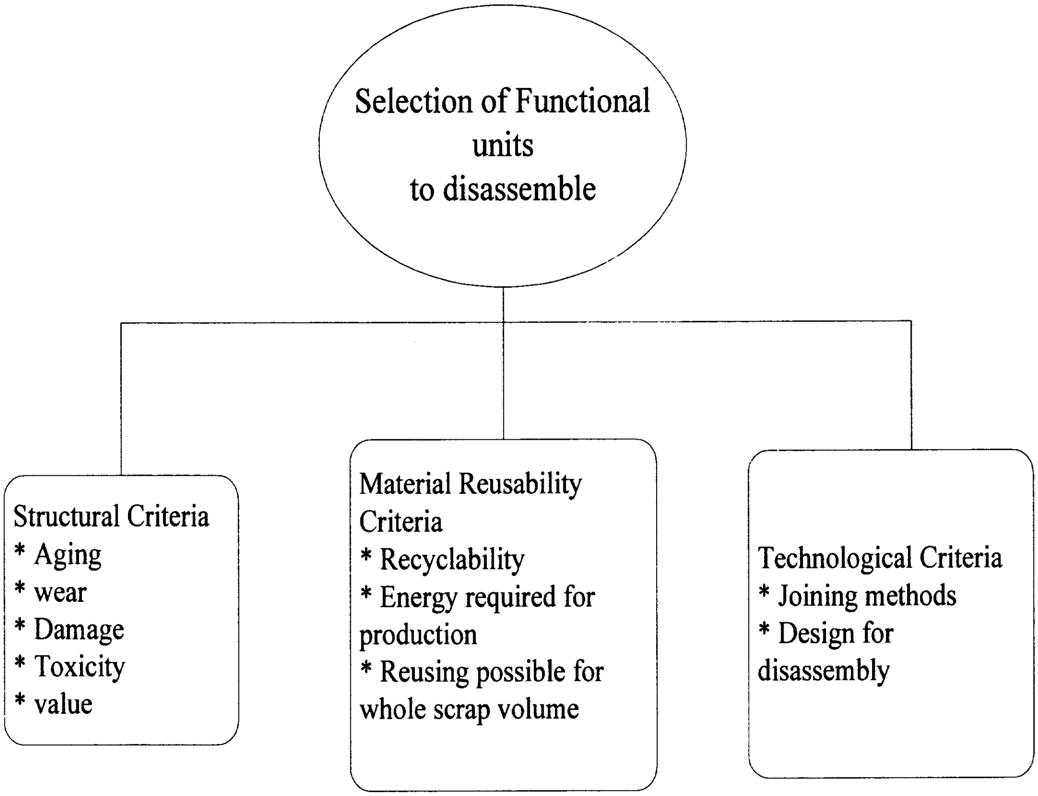


Figure 1.2 Selection criteria for parts and subassemblies to disassemble [6].

1.3 Material Recovery

Outputs of disassembly process are small parts, group of parts or subassembly of product. These parts or subassemblies are disposed, composted or sent for recycling. Disposal of the product is nothing but sending it to a landfill and so it's not considered as good option due to its worst effects on environment. Composting is the controlled, biological decomposition of organic materials into a relatively stable human-like material [28]. Recycling process involves collection, separation and process that returns material passed through recycling process to economic cycle again to be reused in form of raw materials or finished goods. Recycling process helps environment in two ways, one by reducing materials to be land filled and the other is less extraction of natural resources as raw materials. Material recovery by recycling process is carried out either by reusing the parts or remanufacturing them. Possible options available for the product at its end of life are shown in following figure.

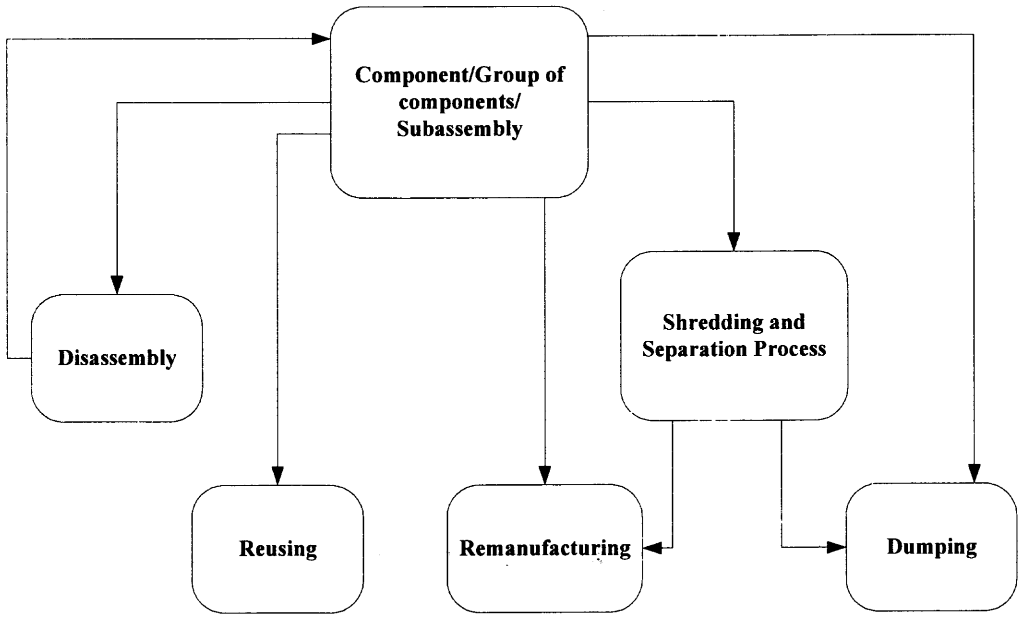


Figure 1.3 Options at product end of life [8].

Reusing of product is the use of product in a new form and may be in new application after its being declared dead from its original application or product. It may require few processes to be carried out on it like cleaning, polishing or refurbishing to make it available for new application. Reusing of product may be restricted by the condition of product like wear, damage or material fatigue. Compare to plastic materials, metals are profitable to be reused while in case of plastic material, cleaning, reprocessing process add considerable cost compare to cost of production of new material.

Remanufacturing is a process in which reasonably large quantities of similar products are brought into a central facility and disassembled parts from specific product are not kept with that product [12]. These parts need processes like cleaning, inspection after being separated by part type.

The different steps involved in a remanufacturing process are check in, disassembling, inspecting, sorting, cleaning, reconditioning, reassembly, control, testing and packaging [9]. Types of processes listed above are needed to remanufacture a product depend on its structure and application. Economy is the vital part to be considered for remanufacturing product. Therefore, disassembly process is crucial among all processes listed above because it impacts on final economy of remanufactured product by its extent of ease and time duration for completion.

Various tasks carried out in disassembly process is shown in following figure.

Unscrew	Remove	Hold/Grip	Peel
Turn	Flip	Saw	Clean
Wedge/Pry	Deform	Drill	Grind
Cut	Push/Pull	Hammer	Inspect

Figure 1.4 The standard disassembly tasks [5].

1.4 Research Objectives

Product disassembly still not accepted in industrial practice as it should be. According to industrial data, around 15% parts of a whole product are recovered for reusing or remanufacturing while remaining 85% are ended up with land filled. The prime hurdles of disassembly process being accepted in usual industrial practice are tremendous manual efforts and energy it asked for.

The disassembly process plan has certain similarity with assembly process plan. As efficient assembly process plan is necessary to build efficient and cost effective assembly operation, efficient disassembly process plan is critical to make disassembly operation efficient in a way to get maximum profit and part reclamation. In assembly process planning, series of steps are specified by which product is assembled from its parts. While in disassembly process planning problem (DP3) feasible plan for product disassembly is generated and implemented to disassembly facility to get parts or subassemblies from a whole product. Das and Naik has stated that an effective DP3 model must be characterized by, (i) an ability to operate with minimum data about the product's design. (ii) be implemented and executed with minimal time and effort , and (iii) include a standard nomenclature for describing fasteners and tools. Das and Naik have presented a model to visualize disassembly as a multi-step process or plan used to explore valuable asset of product. The process carried out at each step is breaking of connection between mating parts and output of that process is recovery of those connected parts or subassembly. This output subassembly is further disassembled in that way disassembly plan have few branches all consists of several steps in each. By seeing this nature of disassembly process planning, it can be seen as network of possible disassembly plans. A disassembly plan is described by the sequence of processing steps, the part or fastener worked on each step, and the part portions, parts and subassemblies remaining at the end [12].

One of the necessary requirements for successful carrying out disassembly process is to make disassembly bill of material (DBOM). The information carried out by DBOM is the physical structure of product in context of disassembly. As it known as a prime requirement for efficient disassembly of product, without DBOM, it's pretty tough to achieve available values inside the product. Other factors affecting the disassembly profitability are information regarding material composition of the part or its reuse value and in some cases possible hazard occurrence at product disposal. Disassembly process is mainly driven by separating two parts or subassemblies by removing fasteners. So, the product fastening structure is a key parameter in the development of a disassembly plan and must be adequately described in the DBOM [12]. Its not possible to get access of all parts of product at first step of disassembly process plan as these few parts are enclosed and can not be accessed directly. It can be separated only when its exposed to dissembler after removing frontal parts. So, this fact can be presented by restricting parts and should be included in DBOM. So, this approach was used by Das and Naik to propose manual process plan. After that Das and Sarat have introduced automatic product disassembly plan. Methodology for automatic disassembly products that helps in building disassembly lines similar to that available for both manufacturing and assembly. The metrics of disassembly to calculate disassembly economics was also developed which inturn calculate disassembly efforts required to separate product into its parts. Software tool was developed to decide final value of revenue generated by disassembling the product.

The purpose of this research is to calculate disassembly economics of different electronic products using automatic disassembly process plan approach. To carry out purpose of this research, previously developed framework of disassembly rules are used to develop process plans for products under research interest.

Thus the prime objectives of this research are

- Generate disassembly process plans for different electronic equipments under study.
- Calculate disassembly economics and thus determine value gained by reusing and recycling of various components of product.
- Illustrate the advantages of automatic disassembly process plan generation approach to be useful for disassembling general electronic equipments.

CHAPTER 2

LITERATURE REVIEW

As government and people grown aware of ecological condition, issue of reducing environmental burden imposed by used and discarded products become outstanding. As the emphasis for prevention of pollution is growing on, the production of environmentally safe product is now both a business and technological issue [12]. One product can have impact on environment almost in its entire life cycle starting from raw material extraction to end of life. Environment restrictions imposed by government and consumer insistence are forcing manufacturers to become more responsible for the safe disposal and recycling of used products.

Since public concerns about diminishing natural resources, limited landfill space and hazardous waste disposal has prompted legislators to place the responsibility for product recycling on the product manufacturers must create products which can facilitate the efficient recovery and reuse of materials and components [5]. So, due to increasing concern for environment issue, disassembly field has attracted increasing attention in the research area. Jovane et al. [1993], Penev and Ron [1996], Boothroyd and Alting [1992], and Gupta and McLean [1996] have studied Design for Assembly (DFA) methods and discussed research opportunities in Design for Disassembly (DFD).

Sandborn et al. [1996] have studied Design for Environment (DFE) and presented where electronics industry standing with respect to DFE and how it can be incorporated the function in everyday work practice, implementing its principles and utilizing tools. Moyer and Gupta [1997] provided different aspects of product disassembly.

The product which can be disassembled with maximum profit among other products competing with it for best suitable product for disassembly will be at the top list. So, any product is evaluated for estimating cost, possible time to disassemble it and design features in context of disassembly process. Dewhurst and Subramani [1991] have studied DFD approach which has ability to quantify assembly cost in its early stages of design and generated metric which is able to establish ratings of product assembly with respect to its expected lifetime servicing cost. Disassembly diagram (DAD) is a representation of the assembly suitable for the generation of disassembly sequences [12]. So, algorithm developed my Dewhurst and Subramani get knowledge from model and represent in the form of the DAD. DAD has made automation of disassembly line easier.

Hrinyak et al. [1996] have examined different existing software tools and studied which is the best to implement into design phase to make design best for disassembly using case study. They have used software tools like

- Design for disassembly
- Activity-Based Costing Demanufacturing model with uncertainty
- Life-cycle Assembly, Services and Recycling
- DIANA Disassembly Analysis

They compared results for four separate comparisons of the data output models: assembly, disassembly time, design changes and retirement cost.

Later Pnueli and Zussman [1997] developed new algorithm for design-for-recycling problem and then quantitatively evaluated end of life value of product using this new algorithm. Kroll [1996] proposed a method to evaluate product design for recycling and environment friendly quantitatively. He uses work measurement analysis of standard disassembly tasks and developed means of identifying design weakness with respect to disassembly process.

2.1 Research Approach and Objective

There are few references provides information regarding disassembly cost estimation. Purpose of this research deals with disassembly cost as well as disassembly process plan generation. Das and Naik have proposed model which includes both disassembly cost estimation and disassembly process plan generation. Later Das and Sarat used this approach to introduce automation in disassembly process plan generation. They developed user friendly tool to generate disassembly process plan as well as decide net profit and cost occurs in carrying out disassembly operation. Main purpose of this research is to develop disassembly process plans for several electronic equipments using tool developed by Das and Sarat and to assess them with respect to disassembly economics. The main aims of this research are

- Generate disassembly process plans for various electronic equipments.
- Calculate efforts/costs and net profit occurs from disassembly of these products.
- Compare two approaches of manual disassembly process plan generation and automatic process plan generation.
- Establish suitable approach as a most advantageous among available approaches.

CHAPTER 3

DISASSEMBLY ECONOMICS AND RULES

Disassembly concept get all important because of its ability to provide good value by reusing and recycling product parts as well as its sensitivity for environment problems. It contains basically two principal operations named unfastening and disassembly. Disassembly plan is a systematic approach to carry out disassembly process in such a way that it gives profit from disassembly process by reusing, recyclable parts. Disassembly plan consists of steps and each step has certain activity like unfastening, disassembly or part disposal. So, output of each step of disassembly plan is a part, group of part or subassembly of product. So, each step has its own values of efforts that can finally express economical gain or loss of disassembly process of whole product.

3.1 End Results Of Disassembly Process

As, disassembly is a process of dismantling product into components the output of disassembly process are various components having qualities to be reused, recycled or they need to throw in trash as waste material. Criteria for reusing and recycling components have been decided in the beginning. According to set up criteria to reuse and recycle material, various out put bins are introduced. Recover components from products are collected into bins according to their material impurities and specifications like maximum allowable impurities and minimum acceptable volume set for each bin. Material impurity level of component decides value of component in other words quality of component and by that market value of component.

Let B=0,..., b be the material output bins, were decided to keep in a facility. Here bins 0 has been assumed as reuse bin and bin b as waste bin. For each part with reuse potential, let R_i be the reuse value. For parts with no reuse R_i=0. It was already set criteria for reusability of parts and their market values. Note that the part reuse value is net of any cleaning, refurbishment, and inspection costs. Let C_b be the market value of a bin per unit weight. For the waste material bins, C_b will have a negative value indicating a disposal cost. Let ξ_B be the maximum allowable material impurity in a bin. With the help of DBOM parts can be assigned to candidate bins that can give maximum value from that part. Often there is only one candidate bin. Let Φ_{iB} be the recyclable purity of a part when assigned to a bin, this is always in the 0 to 1 range. For instance a part may have Φ_{iB}=0.90 when assigned to the Copper high bin implying it has 10% impurity level relative to that bin. The same part may have Φ_{iB} =0.95 when assigned to the Copper mix bin. Typically only a couple of the Φ_{iB} values for a part will be non-zero. A part can only be assigned to a bin if 1- $\Phi_{iB} < \xi_B$. When a carcass is disposed then the weight average purity is used instead.

Let ω_i be the weight and ζ_i be the purity level of part i. Then the value gained from disassembly is given by

$$Value = \sum_{i=1}^{L} R_i + \sum_{i=L}^{N} \omega_i \cdot \zeta_i \cdot \phi_{iB} \cdot C_b$$

Where L parts were sent to reusable bin and remaining N-L parts were sent to material bins. This can be taken for the value output from a disassembly process plan.

But since some of the parts have considerable hazard mitigation values, the total value of the disassembly process plan is given by

$$TotalValue = \sum_{i=1}^{L} R_i + \sum_{i=L}^{N} \omega_i \cdot \zeta_i \cdot \phi_{iB} \cdot C_b + \sum_{i=1}^{N} H_i$$

Where H_i represents the hazard mitigation value of part i.

3.2 Disassembly Effort

Effort requirements are different for each step of disassembly process plan dependent on number of fasteners, the type of fastener and the type of disassembly process being used. It was found that disassembly effort and cost was a function of several factors, much like an assembly process [12]. Das et al. proposed seven weighted factors needed for generate a reliable estimate of the disassembly effort and cost. Action based costing approach was used to propose these factors. Having tested using industrial data, the weighted factors are valid which are fixed for each factor. These seven factors known as metrics for a disassembly process.

3.2.1 Effort Metrics

- Time: The disassembly time for each step is time taken to complete whole operation assigned for that step. Labor cost and so profit margin proportionally related to disassembly time as it is a manual process. It is having major share of proposed scale by having the highest weighing of 25%.

- Tools: Tools include all equipments and other handling device participates in disassembly step. Tooling cost is not among those significant costs so, it got relatively lower weighing of 10% in the scale.

- Fixture: Fixture is a part holding the object that makes disassembly process easier. It is related with set up time as set up time increases, fixture cost goes on.

Fixturing costs have relatively moderate weighing of 15% as it refers to set up time

- Access: Part can be anywhere in the product. It may restricted by other part. Access represents part accessibility of part in product. Access is having weighing of 15% in the scale.

- Instructions: Variety of products at disassembly facility and design variations in similar types of products make necessary to train disassemblers to carry out disassembly process with low cost and less time. Instructions are not significant cause of disassembly cost and so having less weighing of 10% in the scale.

- Hazard Protection: Output of disassembly process is broken parts and main activity of disassembly process is to break the joints between parts. Broken parts may be hazardous for example battery acid. Hazard represents cautions regarding danger that occurs with hazardous parts and trains disassembler how to protect him from them. It has relatively low weighing of 5% in the scale.

- Force Requirements: Disassembly is basically forceful activity. Almost all kinds of activities included in disassembly activity like breaking welded joints by hammering, removing screws using screw driver, force must be exerted. Either man or machine are employed to carry out this forceful activity. Force requirement has weighing of 20% in the scale.

Following figure shows distribution of seven effort factors in total effort score.

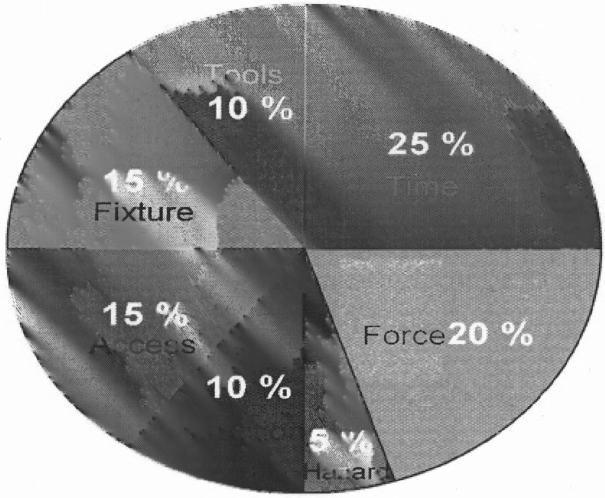


Figure 3.1 Distribution of effort factors.

3.2.2 Effort Value

The total score of disassembly step is sum of individual score of each seven factors. Score of each metric represents the difficulty rating of disassembly process. Higher the scores mean it takes relatively more efforts to carry out that operation and hence relatively cost will be higher.

Direct labor effort and indirect labor efforts are two branches of the total disassembly effort. Cost associated with labor requirements, wages and other labor charges make direct labor effort. While indirect labor effort considers the overhead costs. The time takes part in calculation of direct labor effort at the same time sum of scores of all seven factors are used to calculate indirect labor effort.

$$directlaboreffort = \frac{\alpha * time}{3600}$$

$$Indirecteffort = \frac{\beta * sumofscore * \alpha * 3}{3600 * 100}$$

Where α = direct labor effort coefficient

B = indirect labor effort coefficient

The total disassembly effort is a sum of direct and indirect labor efforts. Therefore, total disassembly cost is calculated as:

Total disassembly effort = direct labor cost + indirect cost

3.3 Disassembly Economic Analysis

The product is considered for disassembly if it going to return some value from its part. So, soul aim of disassembly process is to make it some profit from used parts and recyclable parts of product. To carry out disassembly operations certain costs occur like labor, facility, equipments, expertise. Therefore, disassembly process can be profitable if value achieved from parts should be greater then all expenses occur during disassembly operation. We can estimate net revenue, C_{NR}, gained from the disassembly process plan from disassembly process using above discussed costs and gain. Let C_{DR} be the out put revenue and C_{DC} be the total cost for a disassembly process plan. Then,

$$C_{DR} = \sum_{i=1}^{L} R_i + \sum_{i=L}^{N} \omega_i \cdot \zeta_i \cdot \phi_{iB} \cdot C_b + \sum_{i=1}^{N} H_i$$

$$C_{DC} = \frac{\alpha}{3600}(T + 3 \cdot S \cdot \beta)$$

Where T – disassembly time

S – Sum of scores of seven effort metrics.

$$C_{NR} = C_{DR} - C_{DC}$$

Let σ denote the disassembly return on investment, then:

$$\sigma = \left(\frac{C_{DR}}{C_{DC}} \right) - 1$$

Negative value of σ represents disassembly process as not profitable process. Therefore, σ provide necessary standard to compare different disassembly plans for same product.

CHAPTER 4

DESIGN INPUT AND DISASSEMBLY RULES

4.1 Design Input

Design input includes design data about the original product that is being disassembled. As it was mentioned in previous chapters that the disassembly bill of material (DBOM) is generated which represents data of product in context with disassembly. In other words disassembly bill of material transforms data of product from product manufacture to consumer and the end of life disassembler. Mainly fastener types, number of fasteners, mating relationship and restricting parts get focused during entering data in disassembly bill of material (DBOM)

There are few criteria regarding entering part data into DBOM. According to the material homogeneity, group of parts are considered as one part or subassembly (e.g. Automobile engine). Sometimes it can be wise decision to discard a subassembly having several parts connected in it due to hazardous condition it posses. (e.g bettery). Similarly due to complex types of joints like welded and soldered joints, it is better not to break these joins and to dispose whole subassembly.

For each listed part the disassembly bill of material (DBOM) provides information regarding its weight, material content, purity and data about any hazard content present [12].

Prime activity carried out in disassembly process is to removal of fasteners to dismantle two pats connected with several fasteners. There for information regarding fasteners should be very clear with disassembly as it gets maximum focus all the time in disassembly process. Information regarding fasteners in design data includes fasteners sets, types of fasteners and number of fasteners in each set. Further fastener types are divided into separate and integral fasteners. Das et al. [2000] have proposed experimentally derived data of U-Rating for each type of fasteners, which basically represents relative unfastening difficulty. All types of fasteners with their U-Rating are listed in following figure.

Table 4.1 Fastener Types With U-Rating [4]

SEPARATE FASTENERS			INTEGRAL FASTENERS		
Code	*Fastener Type*	*U-Rating*	*Code*	*Fastener Type*	*U-Rating*
1	Nail with head	1.5	13	Cylindrical Snapfit	1.6
2	Nail w/o head or Pin	1.8	14	Cantilever Snapfit	1.3
3	Screw/Bolt standard head	1.4	15	Seam/Crimp Joint	1.6
4	Screw/Bolt specialty head	2.2	16	Interference Fit	1.8
5	Nut & Bolt	2.1	17	Integrally Threaded Part	2.2
6	Rivets/Staples	2.0	18	Socket and Plug	1.2
7	Retaining Rings/Circlips	2.5			
8	Tape	1.7			
9	Adhesive	2.1			
10	Welded	4.0			
11	Velcro/Zipper	1.0			
12	Releasable Clips	1.8			

Parts are connected with other parts via fasteners and establish specific mating relationship. Mating relationships of several parts of products are important design data that help in generating disassembly bill of material. Part accessibility with its restricting parts can be establishes using data of mating relationship. Access to the unfastening head or trigger is a key factor in determine both a disassembly plan and the effort associated with implementing that plan [12].

Das at el. [2002], developed topology for unfastening access. Six possible levels of access difficulties were introduced. Following figure illustrate all six topology.

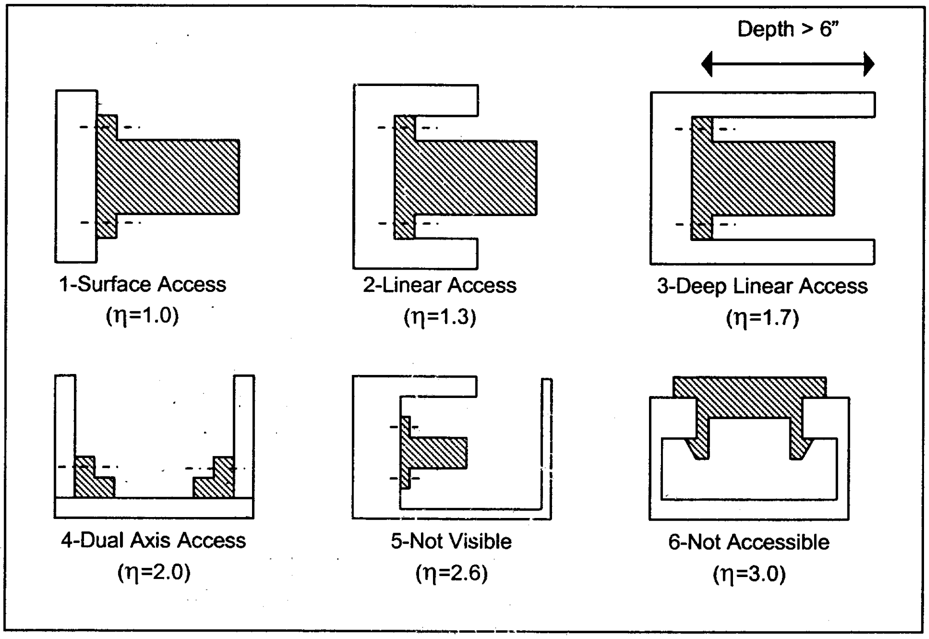


Figure 4.1 Fastener access topology [4].

Finally, to create sequence of disassembly plan, design data of restricting parts help a lot. Restricting parts are basically those parts which limit the access of certain parts. Therefore, restricting parts need to remove first in disassembly process to reach the part of interest.

4.2 Set Of Rules

It is necessary to have set of rules to determine the action to be done in a given step of process plan while generating automatic process plans for disassembly. Das and Sarat have proposed set of six rules which are simple and executable at every step of disassembly process plan. Each one of the rule focuses on different perspective of disassembly [12].

Score of each rule was normalized using average part value in the design i.e B. Z is maximum possible value of the design. Value of B can be achieved by dividing value of Z with half the total number of parts which includes parts as well as fasteners. This B is used as score normalizer.

Few variables are needed to calculate before each step. These variables are average value of the design B, average part value of the design at step l, B_l, total value of the design Z, and the value of the design at step l, Z_l.

The total value of design Z is calculated using the formula

$$Z = \sum_i Max(V_{ij})$$

Where i – *Number of parts.*

j – *Number of bins.*

V_{ij} – *Value of part i when assigned to bin j.*

The average part value, B is calculated based on Z. The formula for B is

$$B = Z/(N/2)$$

Where Z – *Total value of design.*

N – *Total number of parts. (Both parts and fasteners are considered)*

The average part value at each step, *l*, is calculated by subtracting the value of the parts retrieved prior to that step from Z. Therefore, B_i is given by

$$B_i = \frac{Z_i}{(N/2)}$$

Where B_i – *Average part value at step i.*

i – *Number of step.*

Z_i – *Total Value remaining in the design.*

N – *Total number of parts.*

The effort to remove a fastener is calculated using formula based on the access, number of fasteners, U-rating and restricting parts.

Formula for calculating effort is given by

$$Effort = [(Urating + Access) * NumberofFasteners] + Numberof\,\mathrm{Re}\,stricitingParts$$

Bin assignment and effort analysis are final processes before completing process plan. In bin assignment retrieve parts are assigned to bins manually and in effort analysis, those seven factors are set for each step.

Retrieved bin value is a value of parts after they are assigned to certain bins upon their retrieval.

Final economical value of process plan is calculated using following formula.

Final Value = Retrieved Bin Value+ Hazard mitigation Value – Total Effort

Here hazard mitigation value is a value gained by not allowing a certain part disposed into environment. As there is always certain cost attached with part disposal process due to environment regulations, we can gain some value by not allowing a part to be disposed into environment.

4.2.1 Rule 1: Identify a Carcass for Immediate Disposal

Carcass is identified as a group of parts or subassembly that is created during disassembly process. Carcasses, which are composed of materials, all of which are compatible with each other with a recyclability perspective need not be broken any further unless, some of the parts in them pose a hazard or have a high reuse value when recovered [12]. It takes less effort to dispose a whole carcass then its individual parts. So, to dispose a carcass is comparatively profitable strategy. This rule works on the same principle

This rule scans all existing carcass to see any possibilities to dispose it in one of the material bins. Materially homogenous carcass can be disposed to a compatible bin to gain its recyclate value. Each bin in the facility has a specified purity level. This level specifies the maximum amount of impurities that are allowed. If any of the carcasses formed during disassembly, satisfy this purity level then that carcass can be theoretically sent to that bin.

Here, initially all the carcasses in the design are identified. After that the bin that gives maximum possible value for this carcass is identified. If carcass satisfies the maximum allowable impurity condition of the bin, it can be disposed to that bin.

After identifying the bin that gives maximum value for a carcass, the present impurity of carcass is calculated.

It can be calculated using following formula.

$$\%\,\mathrm{Im}\,purity = \sum_{k} \frac{\{[(1 - Max(0, \alpha_{Mkj}))W_k]\}}{\sum_{k} W_k}$$

and total bin value for carcass i, disposed to bin j.

$$B_{ij} = \sum_{k} \left\{ W_k \cdot P_k \cdot \alpha_{Mkj} \cdot b_j \right\} \forall k \in i$$

Where, B_j – represents the total bin value when carcass i is disposed to bin j.

W_k – represents the weight of part k.

P_k – represents the purity of part k.

α_{Mkj} – represents the value compatibility of part k with bin j.

M – represents the material of part k.

k – represents a part

j – represents a bin.

i – represents the carcass

The value of this rule is given by

$$Value = Max(B_{ij})$$

Where B_{ij} – *The value of carcass i when disposed to bin j.*

i – *Number of carcasses.*

j – *Number of bins.*

The score is calculated using the formula

$$Score = \frac{Value}{0.8 \times Max.ValueofOtherRules}$$

The flow of logic for Rule 1 is shown in following diagram.

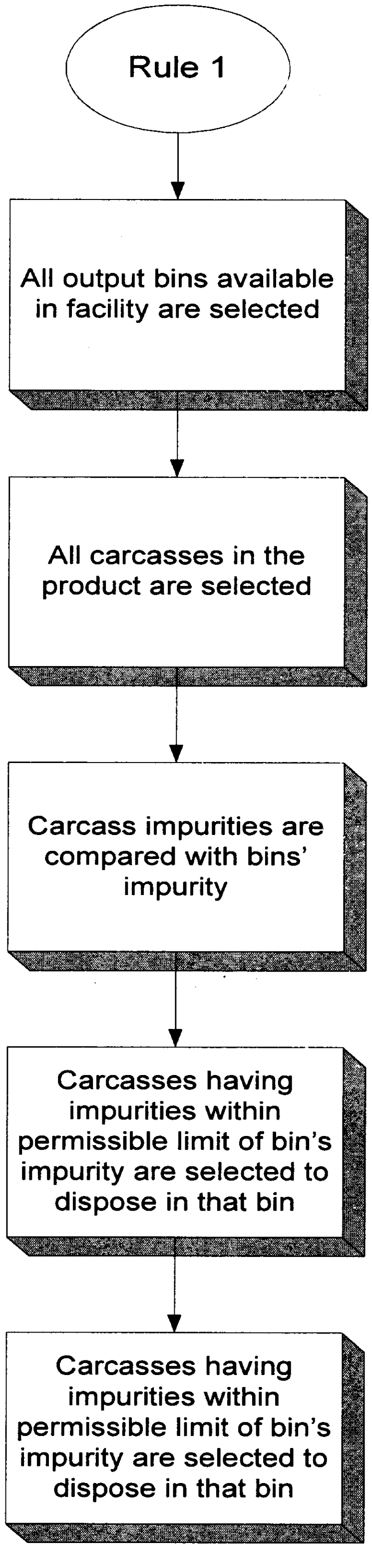


Figure 4.2 Flow diagram for Rule 1.

4.2.2 Rule-2 Identify a Part that on Removal will make a Carcass Materially Compatible

By effort point of view, it is more desirable to dispose whole carcass instead of separate parts. This was the main theme of first rule and hence to identify a carcass that is materially compatible with bins is the prime objective of Rule 1. If Rule 1 is further expanded that is by removing a part, remaining carcass will be materially compatible. This is the objective of Rule 2.

This rule evaluates a carcass in an attempt to identify which parts are blocking their immediate disposal due to high levels of impurity. Removal of the blocking parts will increase the disposal probability of a carcass.

Each part k has a value compatibility with respect to each bin j. This is represented by α_{Mkj}. M is the material of k. This is nothing but the amount of impurity of this material that the bin can hold. This is used to find out which part is to be removed. The part with high weight and low value compatibility will make a carcass materially incompatible. There weight of the part is divided with its value compatibility for each part in carcass. The formula used is $\frac{W_k}{\alpha_{Mkj}} \exists k$.

The part having highest ratio of $\frac{W_k}{\alpha_{Mkj}} \exists k$ is considered as a part to be removed.

The score is calculated using the formula

$$Score = \frac{Value}{Effort \times B}$$

Therefore, removal of this part makes way clear to dispose a whole carcass into bin and hence gaining more profit from disassembly.

Take one example of a carcass made of three parts P1, P2 & P3. Weights of parts are 0.75 lb, 0.37 lb, 0.95 lb, respectively. Parts P1 and P3 are made of steel and material of part P2 is plastic. Now value of steel bin is $ 0.6 and plastic bin gives value of $ 0.20. Now according to criteria of Rule 2, we can select steel bin as a target bin as it gives maximum value among two bins. The α_{Mkj} values of steel and plastic with respect to steel bin are given as 1 and 0.25, respectively. Now, putting all these value in $\frac{W_k}{\alpha_{Mkj}} \exists k$ ratio, we get this ratio for P1, P2 and P3 as 0.75, 1.48 and 0.95, respectively. So, according to this calculation and the rule suggest removal of part P1 to make remaining carcass materially compatible.

The flow diagram for Rule 2 is shown in following figure.

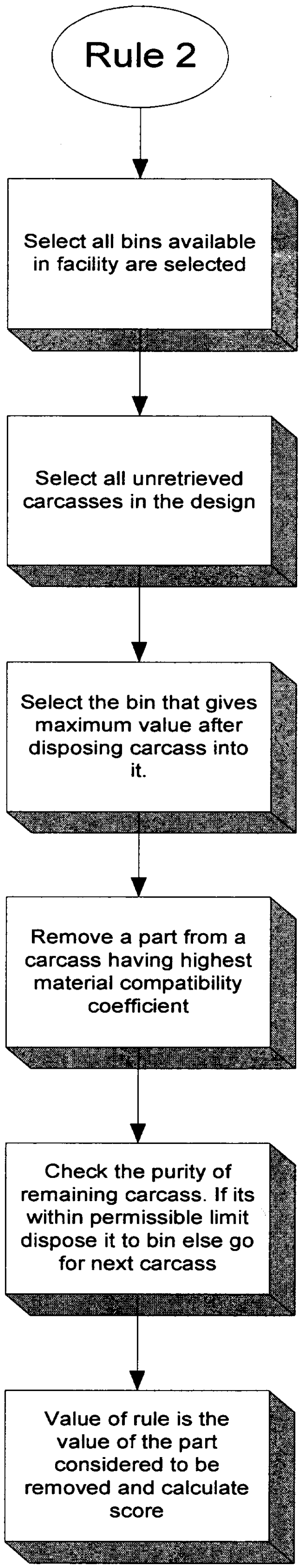


Figure 4.3 Flow diagram for Rule 2.

4.2.3 Rule 3: Identify the Part with High Reuse Profit Potential

Manufacturing cost of material can be reduced by using readily available part into assembly instead of making it into plant. The well accepted motive of disassembly process is to achieve parts from a product that can be used for new product. Therefore, reusing the part will create less effort to disposed it into environment as a waste and can be used to make new part and by this reducing the manufacturing cost of a product. Therefore, to identify parts that can be reused is at highest priority in disassembly process and that is the prime objective of Rule 3.

All non-retrieved parts are evaluated in terms of their value and projected disassembly cost. This cost is derived as a function of the number of current fastening links and the U-rating.

All the parts are scanned for there reuse value by this rule and the part with highest reuse value is identified. This part with highest reuse value is targeted to retrieve. If this target part is restricted by other parts then restricted parts are removed first and then target part is retrieved in successive steps.

The value of this rule is calculated as reuse value of the part. The score of this calculated using the formula

$$Score = \frac{Value}{Effort \times B}$$

Suppose a carcass has three parts with reuse values 1.5, 2.0 and 1.2 units, respectively. If no part restricted the access of these three parts then second part with highest reuse value is identified and considered as a target part to be retrieved. This part will be removed from assembly immediately.

The flow diagram for Rule 3 is shown in following figure.

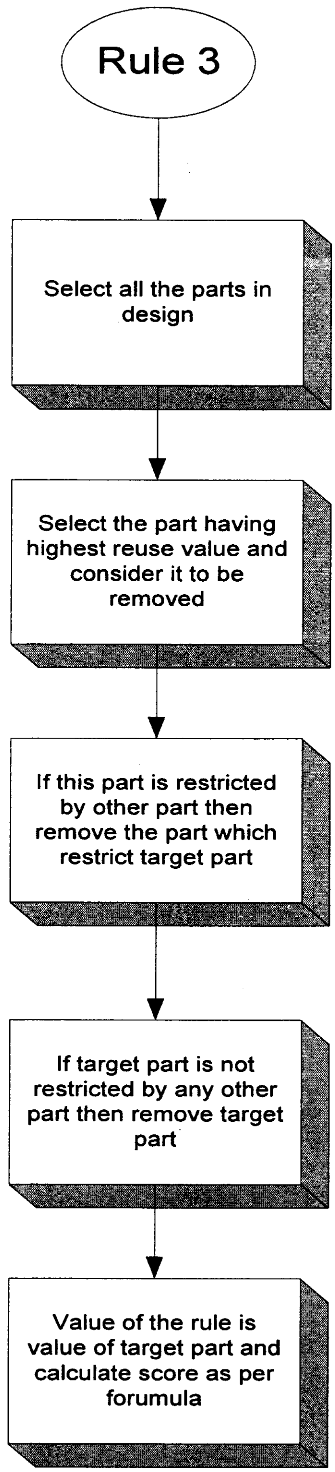


Figure 4.4 Flow diagram for Rule 3.

4.2.4 Rule 4: Identify the Part with Material Value Potential

Due to industrial revolution started since last centuries, scarcity of natural resources was always a topic of concern. Now in manufacturing point of view its always desirable to manufacture a product with less cost. If two materials are compared, one is natural resource that needs to be extracted and other is the recycled material. Its always advantageous to use recyclable material as it costs low and follows all rules set by government regulations. Government encourages recycling of materials so many materials are recycled these days. It is always advisable to recycle material which is scarcely available in nature and which has high value.

There are many parts of different materials in a product and each part has its own material value. Therefore, part with high material value should be retrieved as it is more useful then other parts.

This is the prime objective of Rule 4. All non-retrieved parts are evaluated in terms of their material value and projected disassembly cost. The rule works similar to #3, with only the material value being used instead of the reuse value. Then the recommended disassembly action and corresponding score for the rule is calculated.

The score of this rule is calculated by using following formula.

$$Score = \frac{Value}{Effort \times B}$$

Suppose a product has five parts A, B, C, D, and E. The weights are 0.5lb, 1.2 lb, 0.95 lb, 1.7 lb, and 0.65 lb, respectively. The parts A, B, and C are made up of aluminum and parts D and E are made up of plastic material. Suppose the market values of aluminum and plastic be 1.5$ and 0.5$, respectively per pound. Then, the material values of these parts are 0.75, 1.8, 1.43, 0.85, and 0.33, respectively. And suppose D is a restricting part for parts C and E. Then based on our material value rule first the part C is identified as part with highest material value. But since D is a restricting part for C, system will disassemble D in this step and would disassemble C in following steps.

The flow diagram for Rule 4 is shown in following figure.

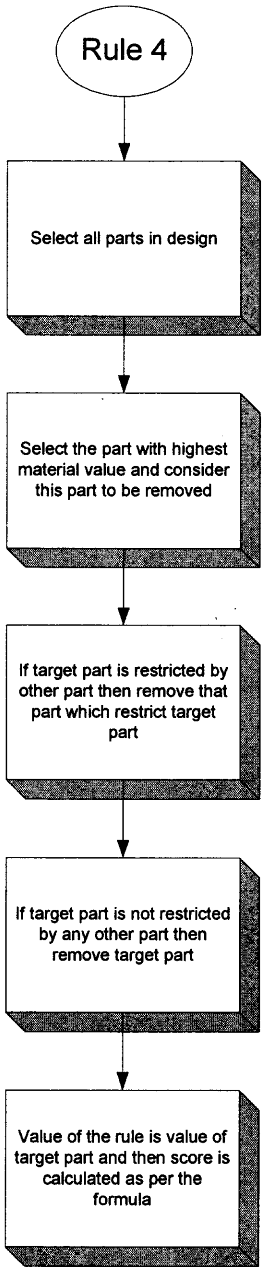


Figure 4.5 Flow diagram for Rule 4.

4.2.5 Rule 5: Identify a Fastener Which Could Generate Additional Carcasses

It is always desirable to work with a whole carcass or to dispose a whole carcass to get maximum profit through less effort. Parts are connected with each other through fasteners. By removing certain fasteners more several groups of parts are formed which are called carcasses. So, its always advisable to generate more number of carcasses by removing one set of fasteners.

Rule 5 works on this principle. This rule identifies fasteners, which on removal will open up the product for easy disassembly of further parts that are in the assembly. This is done by targeting those fasteners that connect an exclusive set of parts. Therefore, they could be removed to potentially generate additional carcasses. Using this principle we can speed up disassembly operation. Therefore, it is advantageous to remove fastener that connects many parts and can generate more number of carcasses after removal.

The value of this rule is Z.

The score of this rule is calculated using following formula

$$Score = \max\left|B_i - B_j\right|$$

Where *i, j* are carcasses generated and

B_i – *Average part value of carcass i.*

Let's take an example. Suppose we have one product in which part A is connected with parts B and C. Part B is connected with 5 parts and part C is connected with 3 parts. The link between A & B is called D and that between A & C is called E. Now, number of links connected with part B is added with D and number of link connected with C is added with E. Number of restricting parts of A, B and C is subtracted from value of D and E to get a final score. The link with such a highest score is considered as a target link to be removed. There can be case like two scores are equal i.e. there is tie between two scores then the difference between the values of carcasses generated from these links is calculated. The link with highest difference is considered for removal.

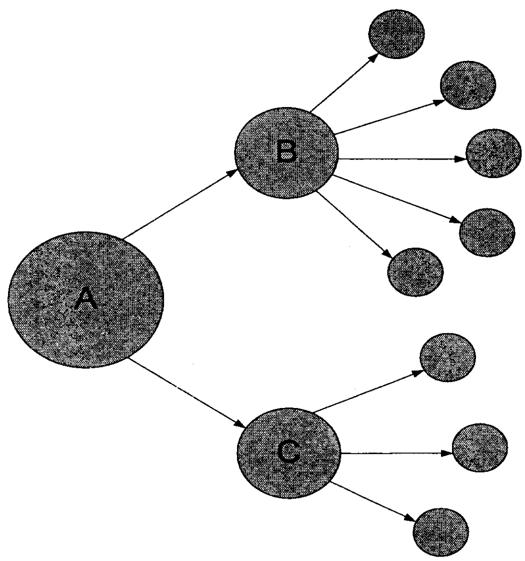


Figure 4.6 Fastening structure of example carcass.

The flow diagram for Rule 5 is shown in following figure.

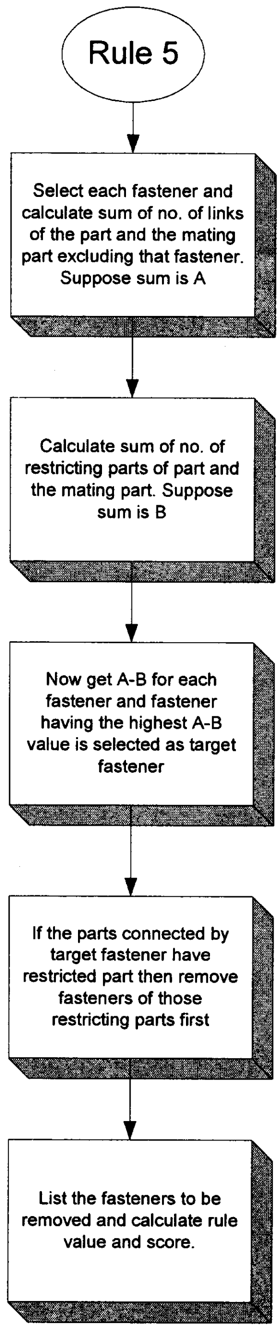


Figure 4.7 Flow diagram for Rule 5.

4.2.6 Rule 6: Stop Disassembly

Measure of successful disassembly plan is the profit it can generate from disassembly of product. It is strictly assessed that disassembly process is giving any profit or not. If loss occurs after disassembling the product then this process is not considered as proper disassembly process. At some point further disassembly is unlikely to generate positive revenue, and it is therefore advantageous to stop disassembly early so as to avoid additional labor costs. We find that as the number of fastening links increases then the disassembly cost increases proportionately.

Rule 6 works based on this principle. It identifies when it is best to stop further disassembly. It uses number of links as a measure to decide about continuation of disassembly process. It assumes that if actual number of links presents in a carcass is greater then 60% of the maximum possible links, then remaining parts should not be disassembled further and they should be sent to trash.

There is one formula to measure possible economic gain from further disassembly. The actual number of links in the products is first calculated. The maximum possible links is given by

$$Max.Links = \frac{N(N-1)}{2}$$ Where, N = number of parts present in the carcass.

Then the ratio of actual number of links to maximum possible links is calculated and is called as δ.

The value for this rule is given to be Z.

The score for this rule is calculated by following formula

$$Score = \frac{B' + Max(0, \delta - C) \times (B - B')}{B}$$

Where, B' – Average part value at that step.

B – Average initial part value.

Z – Maximum possible value of the design.

δ – Ratio of actual number of links to maximum possible links.

C – A constant (0.6 here. As it was assumed 60%).

If the score of this rule is greater then the score of other rules then further disassembly is stopped and remaining parts will be disposed to trash.

The flow diagram for Rule 6 is shown below.

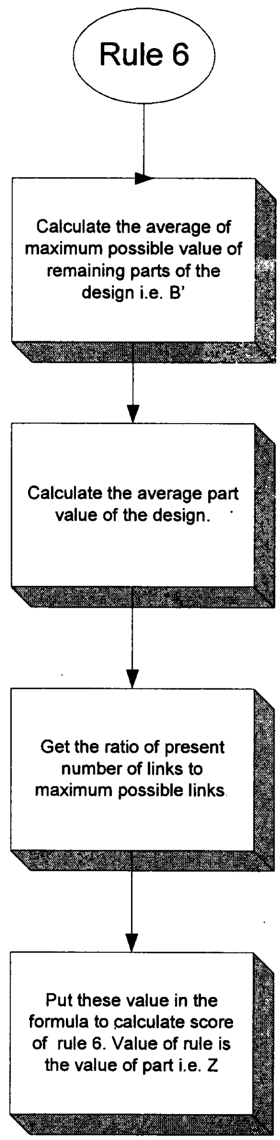


Figure 4.8 Flow diagram for Rule 6.

4.3 Automatic Process Plan Generation

The tool developed by Das and Sarat generate disassembly process plan atutomatically. Here, first score of all rules are calculated for the design. Then rule with maximum score is selected. Action taken based on the rule selected for that step. Action includes removal of fastener and retrieved parts. Once action is completed for first step, again score for each rule is calculated for remaining parts of the design and it follows similar sequence. Disassembly needs to stop when Rule 6 gets selcted as it suggests to stop disassembly and disposed remaining parts to trash.

Das and Sarat has presented the flow diagram for this automatic disassembly process plan generation, which is shown below.

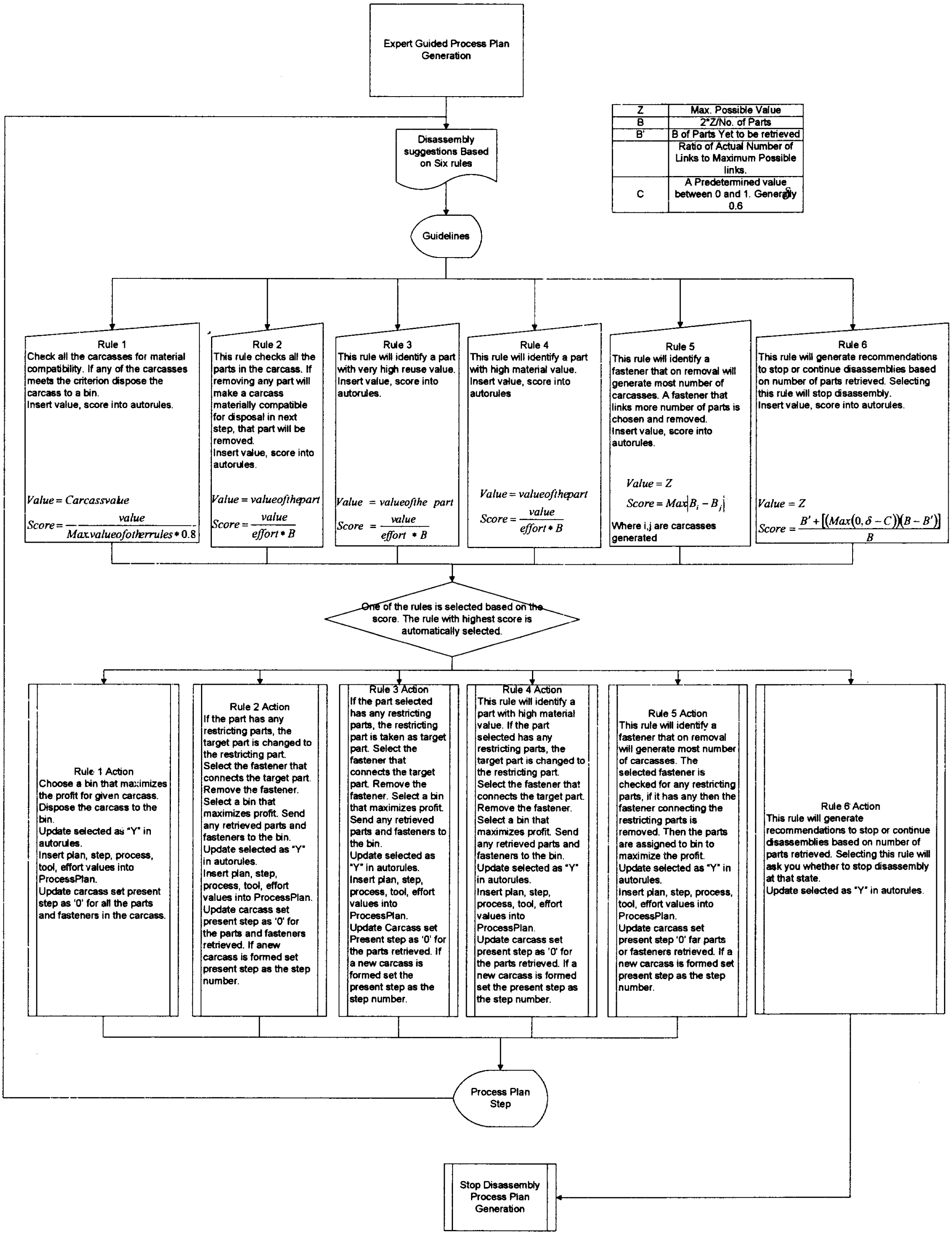


Figure 4.9 Flow diagram for automatic process plan generation [12].

CHAPTER 5

CASE STUDY

5.1 Input Required

5.1.1 Facility Input

Seven output bins have been selected for facility. These bins represent most of the materials that are retrieved during disassembly. The data regarding these is given in the below table.

Table 5.1 Bin Details

BIN NAME	VALUE	MAXIMUM IMPURITY LEVEL
Reusable	$0 per lb	0.9
Steel	$0.7 per lb	0.5
Plastic	$0.6 per lb	0.45
Iron	$0.85 per lb	0.7
PCB	$0.75 per lb	0.4
Mixed plastic	$0.65 per lb	0.75

The value of each bin is determined based on the market rate. Above values are assumptions. Reusable bin will have no value and the parts that are being reused are assigned to this bin. The reuse value of these parts will be the final bin value. The purity levels are determined based on the recycling facility recommendations. The above table shows the data for the seven bins in our facility. Then the material value compatibility is determined for each material compared to all the bins in our facility and is shown in the below table.

Table 5.2 Material Compatibility Values (i)

Bin	Material	Compatibility value	Bin	Material	Compatibility value
Iron	ABS	0.05	PCB	ABS	0.06
	Aluminum	0.2		Aluminum	0.01
	Ceramic	0.1		Ceramic	0.5
	Copper	0.05		Copper	0.001
	Fabric	0.002		Fabric	0.0001
	Ferrous	1		Ferrous	0.001
	Glass	0.01		Glass	0.001
	Glass+Additives	0.03		Glass+Additives	0.002
	Hydrocarbons	0.001		HydroCarbons	0.001
	Mixed Plastics	0.2		MixedPlastics	0.002
	Paper/Board	0.002		Paper/Board	0.04
	PCB	0.002		PCB	1.8
	PET and PVC	0.2		PET and PVC	0.002
	Plastics+additives	0.3		Plastics+additives	0.002
	Steel	0.002		Steel	0.4

Table 5.3 Material Compatibility Values (ii)

Bin	Material	Compatibility value	Bin	Material	Compatibility value
Reusable bin	ABS	0.002	MixedPlastic	ABS	0.1
	Aluminimum	0.002		Aluminimum	0.29
	Ceramic	0.2		Ceramic	0.02
	Copper	0.002		Copper	0.2
	Fabric	0.002		Fabric	0.001
	Ferrous	0.002		Ferrous	0.1
	Glass	0.25		Glass	0.25
	Glass+Additives	0.002		Glass+Additives	0.01
	HydroCarbons	0.002		HydroCarbons	0.001
	MixedPlastics	0.002		MixedPlastics	2
	Paper/Board	0.004		Paper/Board	0.002
	PCB	0.004		PCB	0.002
	PET and PVC	0.004		PET and PVC	0.2
	Plastics+additives	0.004		Plastics+additives	1.7
	Steel	2		Steel	0.72

Table 5.4 Material Compatibility Values (iii)

Bin	Material	Compatibility value	Bin	Material	Compatibility value
Plastic	ABS	0.03	Steel	ABS	0.05
	Aluminimum	0.4		Aluminimum	0.35
	Ceramic	0.001		Ceramic	0.03
	Copper	0.1		Copper	0.25
	Fabric	0.02		Fabric	0.03
	Ferrous	0.15		Ferrous	0.45
	Glass	0.05		Glass	0.02
	Glass+Additives	0.001		Glass+Additives	0.03
	HydroCarbons	0.001		HydroCarbons	0.02
	MixedPlastics	1.7		MixedPlastics	0.4
	Paper/Board	0.01		Paper/Board	0.002
	PCB	0.002		PCB	0.002
	PET and PVC	0.2		PET and PVC	0.002
	Plastics+additives	2		Plastics+additives	0.2
	Steel	0.94		Steel	0.2

After determining the data regarding the bins, the data regarding facility costs or direct labor cost and indirect labor cost were entered. The direct labor cost and indirect cost are calculated based on the variables α, β. These are direct labor coefficient and indirect cost coefficient. The direct labor cost coefficient, α, represents the average labor rate for the facility. It was assumed as \$20 per hour. The indirect cost coefficient, β, represents the indirect facility operations cost as percentage of direct labor cost and its value was assumed as 52%.

5.2 VCR

As electronic equipments are used to explain advantages of developed tool, the next product is RCA VCR, Model No. VR-535.

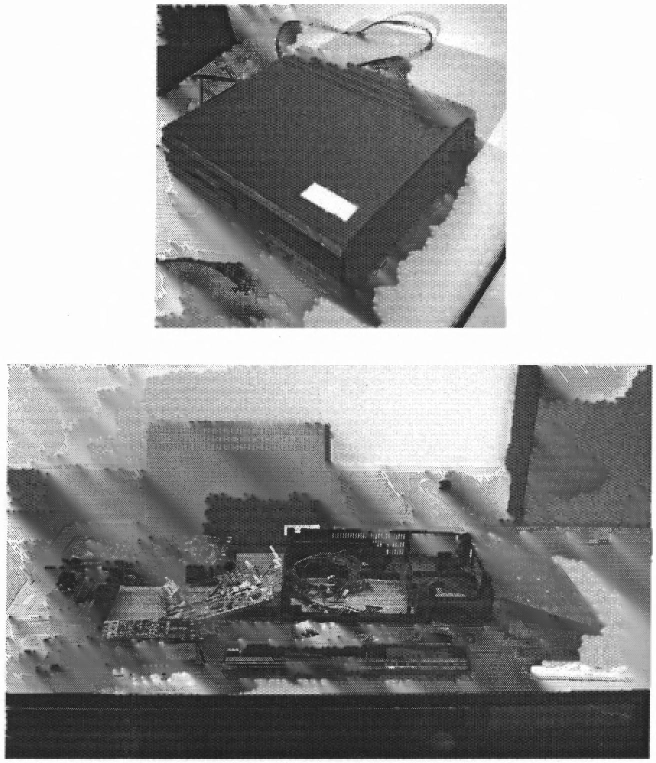


Figure 5.1 Original and disassembled view of VCR.

5.2.1 Design Input

All the product specifications of the VCR unit were entered. The data regarding parts, parts with integral fasteners, and fasteners in the VCR were also entered. The table below shows the data. For a part the typical data includes name, material, weight, purity, reuse value, and hazard penalty. Hazard penalty is the hazardous value possessed by the part. When a part is disassembled gain, equivalent to the hazard penalty is achieved. For example a battery contains dangerous chemicals and should be properly disposed, thus, it has a relatively high hazard penalty. The design data of the RCA VCR computer is given in the tables below.

Table 5.5 DBOM Parts List of VCR

DBOM PARTS LIST				
Part Name	**Material Type**	**Weight (lbs)**	**Reuse Value ($)**	**Hazard Penalty ($)**
Base Plate	Steel	0.65	0.60	0.00
Body Cover	Steel	1.57	1.00	0.00
Carriage	Steel	1.00	0.80	0.00
Chases Board	Steel	1.26	0.10	0.50
Circuit Board	PCB	1.02	0.05	2.00
Connecting Wires	Copper + Plastics	0.15	0.02	0.10
Front Panel	Plastics + Additives	0.26	0.25	0.05
Head	Aluminum	0.64	0.45	0.20
Head Resting Plate	Aluminum	0.10	0.05	0.00
Main Frame	Plastics + Additives	1.05	0.70	0.05
Motor Assembly	Steel	0.36	0.15	1.00
Power Unit	Steel	2.12	0.25	1.50
Rear Circuit Board	PCB	0.04	0.05	0.75
Rear Section Gear Assembly	Plastics	0.04	0.03	0.00
Top Section Gear Assembly	Plastics	0.04	0.03	0.00

Table 5.6 Separate Fastener List of VCR

SEPARATE FASTENER LIST			
Fastener Name	**Material**	**Number of**	**Type**
F1	Steel	2	Screw/Bolt standard head
F2	Steel	1	Screw/Bolt standard head
F3	Steel	2	Screw/Bolt standard head
F4	Steel	3	Screw/Bolt standard head
F5	Steel	2	Screw/Bolt standard head
F6	Steel	4	Screw/Bolt standard head
F7	Steel	3	Screw/Bolt standard head
F8	Steel	3	Screw/Bolt standard head
F9	Steel	2	Screw/Bolt standard head
F10	Steel	3	Screw/Bolt standard head
F11	Steel	3	Screw/Bolt standard head
F12	Steel	4	Screw/Bolt standard head
F13	Steel	3	Screw/Bolt standard head

Table 5.7 Integral Fastener List of VCR

INTEGRAL FASTENER LIST			
Integral	**Integral with Part**	**Number of**	**Type**
Base Plate	Base Plate	2	Cylindrical Snap fit
Connecting Wires	Connecting Wires	4	Cylindrical Snap fit
Front Panel	Front Panel	3	Cylindrical Snap fit

Once the data regarding parts and fasteners were entered, the data regarding restricting parts are entered. Restricting part is the part that limits access to the part in question. For each part a set of restricting parts were identified, whose presence limits the disassembly process. The enclosed parts cannot be removed without removing the cover, so it can be said that body cover is a restricting part for all the enclosed parts. The following table lists all the parts with their respective restricting parts.

Table 5.8 Restricting Parts List of VCR

Restricting Parts List	
Part Name	**Restricting Parts**
Carriage	Body Cover
Chases Board	Body Cover, Carriage
Circuit Board	Body Cover
Head	Body Cover, Carriage
Head Resting Plate	Body Cover
Motor Assembly	Body Cover, Carriage
Power Unit	Body Cover
Rear Circuit Board	Body Cover, Carriage, Chases Board
Rear Section Gear Assembly	Body Cover, Carriage, Chases Board
Top Section Gear Assembly	Body Cover, Carriage

The next data to be entered is data regarding the mating relationships. The mating relationship is determined by the two mating parts and the fastener connecting them. The following table describes all the mating relationships of a CPU.

Table 5.9 Mating Relationship Table of VCR

MATING RELATIONSHIP TABLE			
Mating Part1	**Mating Part2**	**Fastener**	**Type**
Body Cover	Main Frame	F1	Fastener
Front Panel	Main Frame	F2	Fastener
Front Panel	Main Frame	Front Panel	Integral
Circuit Board	Main Frame	F3	Fastener
Carriage	Chases Board	F5	Fastener
Chases Board	Main Frame	F7	Fastener
Connecting Wires	Circuit Board	Connecting Wires	Integral
Power Unit	Main Frame	F6	Fastener
Head Resting Plate	Chases Board	F4	Fastener
Base Plate	Main Frame	Base Plate	Integral
Base Plate	Main Frame	F8	Fastener
Top Section Gear Assembly	Chases Board	F9	Fastener
Motor Assembly	Chases Board	F10	Fastener
Rear Section Gear Assembly	Chases Board	F11	Fastener
Rear Circuit Board	Chases Board	F12	Fastener
Head	Head Resting Plate	F13	Fastener

Diagram of mating relationship with fastener name is shown in following figure.

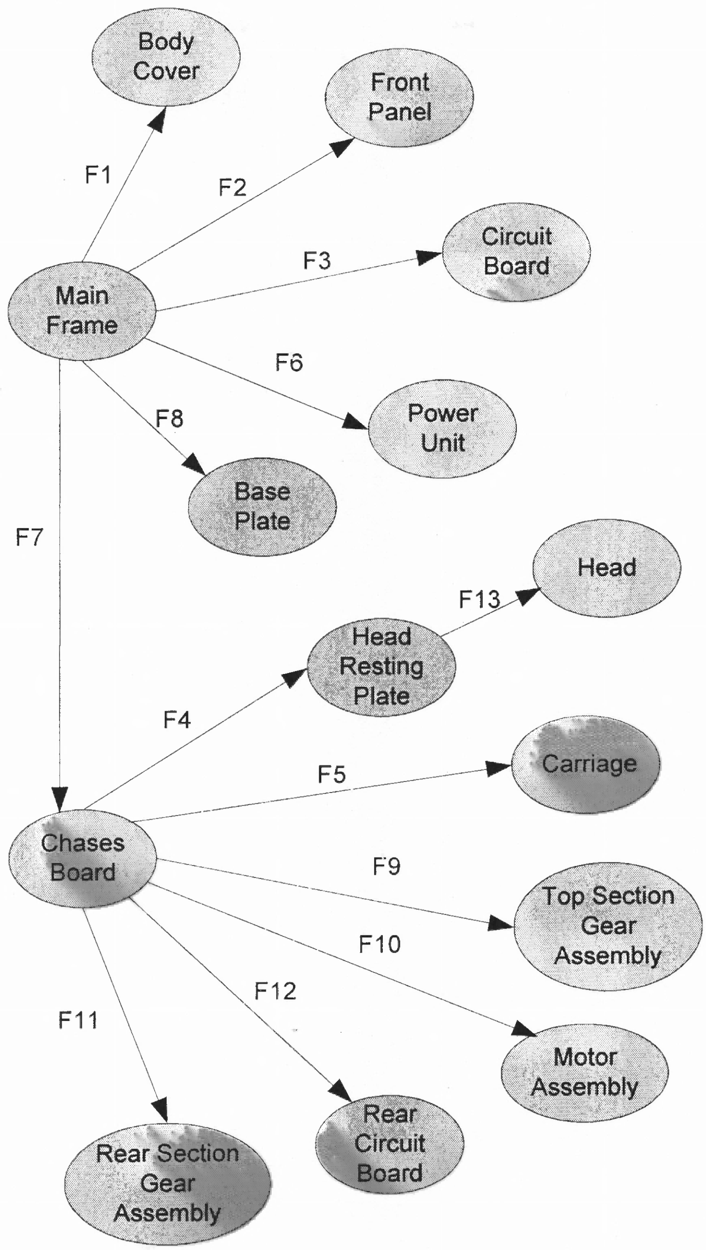


Figure 5.2 Mating relationship diagram of VCR.

5.2.2 Process Plans

First of all manual process plan was generated for VCR. Here, parts are removed entirely by disassembler's own decision.

Table 5.10 Manual Process Plan for VCR

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F1	Unfastening	Manual Screw Driver	36
2	Unfastening	F4	Unfastening	Manual Screw Driver	42
3	Unfastening	F13	Unfastening	Manual Screw Driver	40
4	Unfastening	F5	Unfastening	Manual Screw Driver	41
5	Unfastening	F2	Unfastening	Manual Screw Driver	36
6	Unfastening	F3	Unfastening	Manual Screw Driver	43
7	Unfastening	F6	Unfastening	Manual Screw Driver	40
8	Unfastening	F10	Unfastening	Manual Screw Driver	40
9	Unfastening	F9	Unfastening	Manual Screw Driver	38
10	Unfastening	F7	Unfastening	Manual Screw Driver	44
11	Unfastening	F8	Unfastening	Manual Screw Driver	36
12	Unfastening	F11	Unfastening	Manual Screw Driver	42
13	Unfastening	F12	Unfastening	Manual Screw Driver	44
14	Disassembly	Connecting Wires	Disassembly	Shear Cutter	45
15	Stop Disassembly				0

Table 5.11 Bin Assignment for Manual Process Plan for VCR

Bin Name	Bin Value	Part Name
Steel	5.327	[F1,F4,F13,F5,F2,F3,F6,F9, F10, F7, F8, F11, F12, Body Cover, Carriage, Chases Board, Motor Assembly, Power Unit,]
Reusable	0.65	[Base Plate,]
PCB	0.795	[Circuit Board, Rear Circuit Board]
Plastic	0.138	[Connecting Wires, Top Section Gear Assembly, Rear Section Gear Assembly,]
Mixed plastic	0.8515	[Front Panel, Main Frame,]
Iron	0.629	[Head, Head Resting Plate,]

Next, automatic process plan was generated for VCR. Here, decision of selection of fasteners or parts to be removed is taken entirely by software tool.

Table 5.12 Automatic Process Plan for VCR

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F1	Unfastening	Powered Screw Driver	23
2	Unfastening	F3	Unfastening	Powered Screw Driver	36
3	Unfastening	F5	Unfastening	Powered Screw Driver	35
4	Unfastening	F6	Unfastening	Manual Screw Driver	36
5	Unfastening	F7	Unfastening	Manual Screw Driver	41
6	Disassembly	Main Frame	Disassembly	Shear cutter	38
7	Unfastening	F8	Unfastening	Powered Screw Driver	41
8	Unfastening	F4	Unfastening	Powered Screw Driver	38
9	Unfastening	F10	Unfastening	Powered Screw Driver	36
10	Unfastening	F2	Unfastening	Powered Screw Driver	35
11	Unfastening	F13	Unfastening	Manual Screw Driver	23
12	Disassembly	Connecting Wires	Disassembly	Shear Cutter	36
13	Stop Disassembly				0

Table 5.13 Bin Assignment for Automatic Process Plan for VCR

Bin Name	Bin Value	Part Name
Steel	4.088	[F1,F3,F5,F6,F7,F8,F4,F10,F2, F13,Base Plate, Body Cover, Carriage, Chases Board Motor Assembly,]
PCB	0.795	[Circuit Board, Rear Circuit Board]
Plastic	0.09	[Connecting Wires,]
Mixed plastic	0.9035	[Front Panel, Main Frame, Rear Section Gear Assembly, Top Section Gear Assembly,]
Iron	2.431	[Head, Head Resting Plate, Power Unit,]

Further, semi automatic process plan was generated. Here, software tool shows score of each rule applied and the action to be taken for that rule and for that step. Final decision to select particular rule and action is taken by disassembler.

Table 5.14 Semi Automatic Process Plan for VCR

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F1	Unfastening	Powered Screw Driver	36
2	Unfastening	F5	Unfastening	Powered Screw Driver	40
3	Unfastening	F9	Unfastening	Powered Screw Driver	38
4	Disassembly	Circuit Board	Disassembly	Shear Cutter	42
5	Unfastening	F6	Unfastening	Manual Screw Driver	40
6	Unfastening	F4	Unfastening	Manual Screw Driver	36
7	Unfastening	F13	Unfastening	Powered Screw Driver	42
8	Unfastening	F7	Unfastening	Powered Screw Driver	41
9	Unfastening	F10	Unfastening	Powered Screw Driver	38
10	Unfastening	F2	Unfastening	Powered Screw Driver	42
11	Disassembly	Connecting Wires	Disassembly	Shear Cutter	45
12	Stop Disassembly				0

Table 5.15 Bin Assignment for Semi Automatic Process Plan for VCR

Bin Name	Bin Value	Part Name
Steel	5.047	[F1,F5,F9,F6,F4,F13,F7,F10,F2, Base Plate, Body Cover, Carriage, Chases Board Motor Assembly,]
PCB	0.795	[Circuit Board, Rear Circuit Board]
Mixed plastic	1.001	[Front Panel, Main Frame, Rear Section Gear Assembly, Top Section Gear Assembly, Connecting Wires]
Iron	0.629	[Head, Head Resting Plate, Power Unit,]

5.2.3 Analysis

After entering all the required data, we did the final analysis on all the four process plans. The results are tabulated in the following table.

Table 5.16 Final Disassembly Economic Analysis for VCR

Plan Number	Number of steps	Estimated Disassembly Time (sec)	Direct labor Effort($)	Indirect Effort($)	Retrieved Bin Value ($)	Hazard Mitigation Value ($)	Net Profit ($)
1	14	829.3	4.15	4.42	8.39	6.15	5.97
2	12	532.2	2.66	3.26	8.53	6.15	8.76
2	11	653.7	3.27	3.43	7.47	6.15	6.92

Three plans were observed and the return on investment was calculated to determine which process plan is better. Let σ denote the disassembly return on investment, then:

$$\sigma = \left(\frac{C_{DR}}{C_{DC}}\right) - 1$$

$$\sigma_1 = \left(\frac{8.39 + 6.15}{4.15 + 4.42}\right) - 1 = 0.70$$

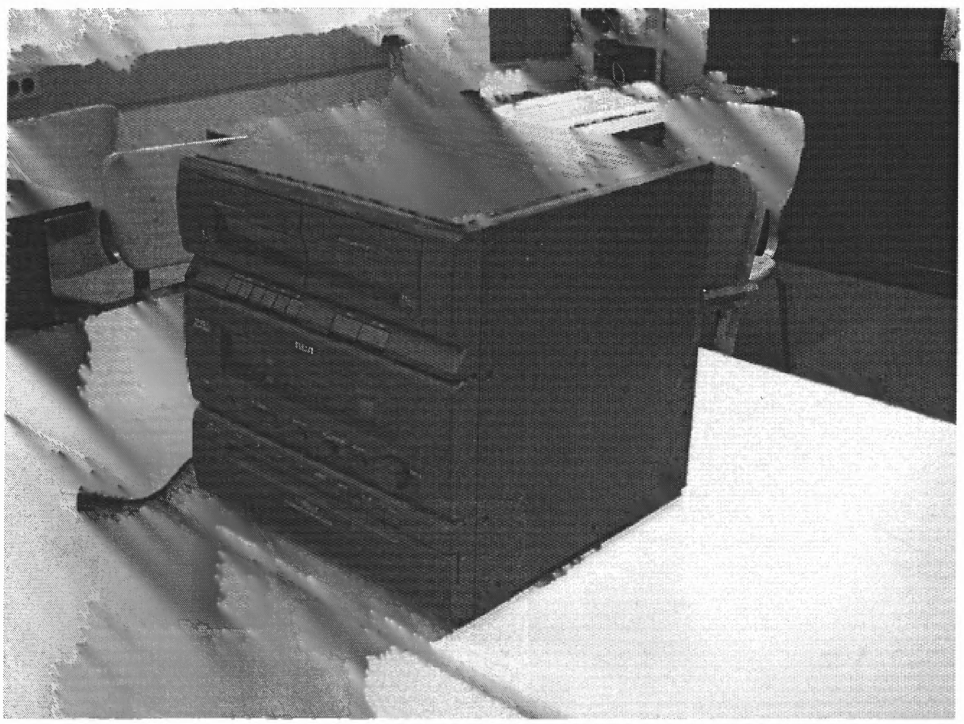
$$\sigma_2 = \left(\frac{8.53 + 6.15}{2.66 + 3.26} \right) - 1 = 1.48$$

$$\sigma_3 = \left(\frac{7.47 + 6.15}{3.27 + 3.43} \right) - 1 = 1.03$$

The above table and later return on investment, shows the automatic disassembly process plan is superior to other modes.

5.3 CD-Player

As electronic equipments are used to explain advantages of developed tool, the next product is RCA, 5 CD Changer with Cassette player and Radio.



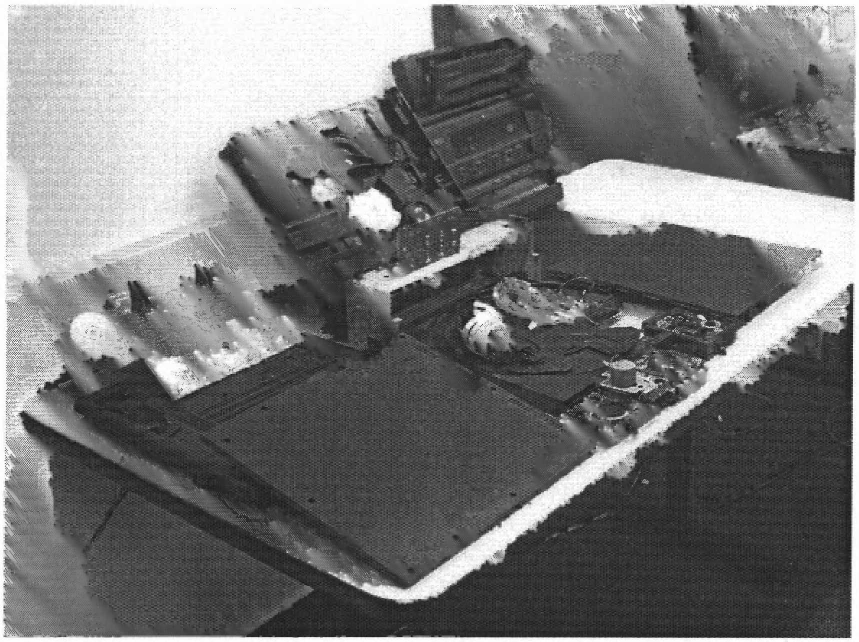


Figure 5.3 Original and disassembled view of CD player.

5.3.1 Design Input

All the product specifications of the CD player unit were entered same as it was done for VCR in previous section. Similarly data regarding parts, parts with integral fasteners, and fasteners in the CD player were entered. The table below shows us the design data for CD player.

Table 5.17 DBOM Parts List of CD Player

DBOM PARTS LIST				
Part Name	**Material Type**	**Weight (lbs)**	**Reuse Value ($)**	**Hazard Penalty ($)**
Base Plate	Plastics + Additives	0.85	0.35	0.10
CD Rotation Plate and Gear	Plastics + Additives	2.90	0.30	0.45
Circuit Boards	PCB	0.85	0.50	1.00
Connecting Wires	Copper + Plastics	0.30	0.10	0.20
Front Panel	Plastics + Additives	1.70	0.50	0.20
Left Cover	Plastics + Additives	0.75	0.50	0.00
Motor and Roller Assembly	Steel	0.80	0.10	0.05
Power Unit Platform	Steel	1.92	0.20	0.70
Rear Cover	Plastics + Additives	1.00	0.45	0.05
Right Cover	Plastics + Additives	0.75	0.50	0.00
Top Cover	Plastics + Additives	0.95	0.40	0.05

Table 5.18 Separate Fastener List of CD Player

SEPARATE FASTENER LIST			
Fastener Name	**Material**	**Number of**	**Type**
F1	Steel	3	Screw/Bolt standard head
F2	Steel	4	Screw/Bolt standard head
F3	Steel	3	Screw/Bolt standard head
F4	Steel	4	Screw/Bolt standard head
F5	Steel	4	Screw/Bolt standard head
F6	Steel	1	Screw/Bolt standard head
F7	Steel	1	Screw/Bolt standard head
F8	Steel	4	Screw/Bolt standard head
F9	Steel	4	Screw/Bolt standard head
F10	Steel	1	Screw/Bolt standard head
F11	Steel	1	Screw/Bolt standard head
F12	Steel	2	Screw/Bolt standard head
F13	Steel	6	Screw/Bolt standard head
F14	Steel	8	Screw/Bolt standard head

Table 5.19 Integral Fastener List of CD Player

INTEGRAL FASTENER LIST			
Integral	**Integral with Part**	**Number of**	**Type**
Base Plate	Base Plate	6	Cylindrical Snap fit
Connecting Wires	Connecting Wires	4	Cylindrical Snap fit
Front Panel	Front Panel	5	Cylindrical Snap fit
Rear Cover	Rear Cover	5	Cylindrical Snap fit

Once the data regarding parts and fasteners were entered, the data regarding restricting parts have been entered. The following table lists all the parts with their respective restricting parts.

Table 5.20 Restricting Parts List of CD Player

Restricting Parts List	
Part Name	**Restricting Parts**
CD Rotation Plate and Gear Assembly	Left cover, Right cover, Top cover, Rear cover, powerunit platform
Circuit Board	Left cover, Right cover, Top cover, Rear cover
Moter and Roller Assembly	Left cover, Right cover, Top cover, Rear cover
Power Unit Platform	Left cover, Right cover, Top cover, Rear cover

The next data to be entered is data regarding the mating relationships. The mating relationship is determined by the two mating parts and the fastener connecting them. The following table describes all the mating relationships of a CPU.

Table 5.21 Mating Relationship Table of CD Player

MATING RELATIONSHIP TABLE			
Mating Part1	**Mating Part2**	**Fastener**	**Type**
Rear Cover	Top Cover	F1	Fastener
Rear Cover	Power Unit Platform	F2	Fastener
Base Plate	CD Rotation Plate and Gear Assembly	Base Plate	Integral
Rear Cover	CD Rotation Plate and Gear Assembly	F3	Fastener
Rear Cover	Left Cover	F5	Fastener
Base Plate	Left Cover	F7	Fastener
Front Panel	Base Plate	Front Panel	Integral
Top Cover	Left Cover	F6	Fastener
Front Panel	Left Cover	F4	Fastener
Rear Cover	Base Plate	Rear Cover	Integral
Front Panel	Right Cover	F8	Fastener
Rear Cover	Right Cover	F9	Fastener
Top Cover	Right Cover	F10	Fastener
Base Plate	Right Cover	F11	Fastener
Base Plate	Power Unit Platform	F12	Fastener
Front Panel	Motor and Roller Assembly	F13	Fastener
Rear Cover	Power Unit Platform	Rear Cover	Integral
Front Panel	Circuit Board	F14	Fastener

Diagram of mating relationship with fastener name is shown in following figure.

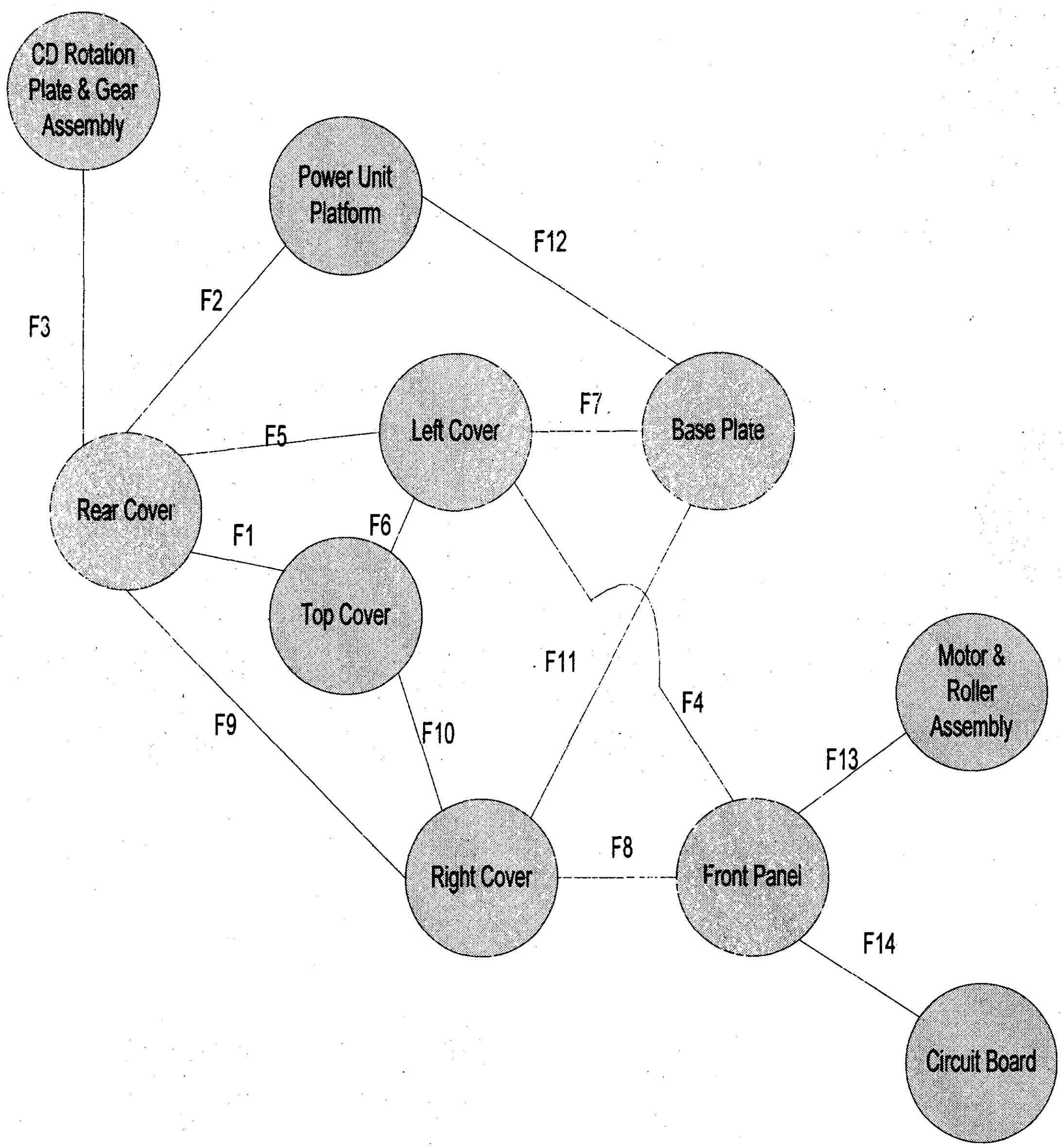


Figure 5.4 Mating Relationship Diagram of CD Player.

5.3.2 Process Plans

Similar to case study of VCR, manual disassembly process plan is generated for CD Player also, which contains 14 steps. The types of part, tool used for particular step and effort used for each steps are shown in following table.

Table 5.22 Manual Process Plan for CD Player

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F8	Unfastening	Manual Screw Driver	36
2	Unfastening	F4	Unfastening	Manual Screw Driver	36
3	Unfastening	F9	Unfastening	Manual Screw Driver	40
4	Unfastening	F10	Unfastening	Manual Screw Driver	41
5	Unfastening	F11	Unfastening	Manual Screw Driver	41
6	Unfastening	F1	Unfastening	Manual Screw Driver	43
7	Unfastening	F6	Unfastening	Manual Screw Driver	40
8	Unfastening	F5	Unfastening	Manual Screw Driver	40
9	Unfastening	F7	Unfastening	Manual Screw Driver	38
10	Disassembly	CD Rotation Plate and Gear Assembly	Disassembly	Shear Cutter	44
11	Unfastening	F2	Unfastening	Manual Screw Driver	36
12	Unfastening	F12	Unfastening	Manual Screw Driver	36
13	Disassembly	Circuit Board	Disassembly	Shear Cutter	45
14	Disassembly	Motor and Roller Assembly	Disassembly	Shear Cutter	44
15	Stop Disassembly				0

Table 5.23 Bin Assignment for Manual Process Plan for CD Player

Bin Name	Bin Value	Part Name
Steel	2.674	[F8,F4,F9,F10,F11,F1,F6,F5, F7, F2, F12, Motor and Roller Assembly, Power Unit Platform,]
PCB	0.6375	[Circuit Board,]
Mixed plastic	5.785	[Base Plate, CD Rotation and Gear Assembly, Front Panel, Left Cover, Rear Cover, Right Cover, Top Cover,]

Next, automatic disassembly process plan is generated for CD Player. It follows same procedure used for generation of automatic process plan for VCR. Information regarding steps and efforts are shown below in following table.

Table 5.24 Automatic Process Plan for CD Player

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F5	Unfastening	Manual Screw Driver	36
2	Unfastening	F8	Unfastening	Manual Screw Driver	36
3	Unfastening	F1	Unfastening	Manual Screw Driver	35
4	Unfastening	F11	Unfastening	Manual Screw Driver	36
5	Unfastening	F4	Unfastening	Manual Screw Driver	41
6	Unfastening	F7	Unfastening	Manual Screw Driver	38
7	Unfastening	F12	Unfastening	Manual Screw Driver	41
8	Disassembly	CD Rotation Plate & Gear Assembly	Disassembly	Shear Cutter	38
9	Unfastening	F6	Unfastening	Manual Screw Driver	36
10	Unfastening	F10	Unfastening	Manual Screw Driver	35
11	Unfastening	F2	Unfastening	Manual Screw Driver	36
12	Disassembly	Connecting Wires	Disassembly	Shear Cutter	36
13	Disassembly	Circuit Board	Disassembly	Shear Cutter	41
14	Unfastening	F9	Unfastening	Manual Screw Driver	42
15	Stop Disassembly				0

Table 5.25 Bin Assignment for Automatic Process Plan for CD Player

Bin Name	Bin Value	Part Name
Steel	1.47	[F5,F8,F1,F11,F4,F7,F12,F6, F2, F10, F3, F9, Motor and Roller Assembly]
PCB	0.6375	[Circuit Board]
Plastic	0.18	[Connecting Wires,]
Mixed plastic	5.785	[Base Plate, CD Rotation Plate and Gear Assembly, Front Cover, Left Cover, Rear Cover, Right Cover, Top Cover]
Iron	1.717	[Power Unit Platform,]

Further, semi automatic disassembly process plan is generated for CD Player is generated in the same way it was generated for VCR. Various steps, tools used in those steps and efforts used for those steps are shown in following table.

Table 5.26 Semi Automatic Process Plan for CD Player

Step Number	Type	Part or Fastener	Process	Tool	Effort
1	Unfastening	F1	Unfastening	Manual Screw Driver	36
2	Unfastening	F6	Unfastening	Manual Screw Driver	42
3	Unfastening	F10	Unfastening	Manual Screw Driver	41
4	Unfastening	F4	Unfastening	Manual Screw Driver	40
5	Unfastening	F7	Unfastening	Manual Screw Driver	40
6	Unfastening	F11	Unfastening	Manual Screw Driver	41
7	Unfastening	F2	Unfastening	Manual Screw Driver	38
8	Unfastening	F8	Unfastening	Manual Screw Driver	42
9	Disassembly	CD Rotation Plate & Gear Assembly	Disassembly	Shear Cutter	38
10	Disassembly	Circuit Board	Disassembly	Shear Cutter	42
11	Unfastening	F12	Unfastening	Manual Screw Driver	40
12	Unfastening	F5	Unfastening	Manual Screw Driver	42
13	Unfastening	F9	Unfastening	Manual Screw Driver	44
14	Stop Disassembly				0

Table 5.27 Bin Assignment for Semi Automatic Process Plan for CD Player

Bin Name	Bin Value	Part Name
Steel	1.33	[F1,F6,F10,F4,F7,F11,F2,F8, F12, F5, F9, Motor and Roller Assembly]
PCB	0.6375	[Circuit Board]
Mixed plastic	5.785	[Base Plate, CD Rotation Plate and Gear Assembly, Front Cover, Left Cover, Rear Cover, Right Cover, Top Cover]
Iron	1.717	[F3, Power Unit Platform,]

5.3.3 Analysis

After entering all the required data, we did the final analysis on all the four process plans. The results are tabulated in the following table.

Table 5.28 Final Disassembly Economic Analysis for CD Player

Plan Number	Number of steps	Estimated Disassembly Time (sec)	Direct labor Effort($)	Indirect Effort($)	Retrieved Bin Value ($)	Hazard Mitigation Value ($)	Net Profit ($)
1	14	917.8	4.59	4.37	9.10	2.60	2.74
2	14	740.8	3.70	4.11	9.72	2.80	4.71
3	13	810.1	4.05	4.10	9.47	2.60	3.92

Three plans were observed and the return on investment was calculated to determine which process plan is better. Let σ denote the disassembly return on investment, then:

$$\sigma = \left(\frac{C_{DR}}{C_{DC}}\right) - 1$$

$$\sigma_1 = \left(\frac{9.10 + 2.60}{4.59 + 4.37}\right) - 1 = 0.31$$

$$\sigma_2 = \left(\frac{9.72 + 2.80}{3.70 + 4.11}\right) - 1 = 0.60$$

$$\sigma_3 = \left(\frac{9.47 + 2.60}{4.05 + 4.10}\right) - 1 = 0.48$$

The above table and later return on investment, shows the automatic disassembly process plan is superior to other modes.

REFERENCES

1. Hrinyak, M. J., Bras, B., and Hoffmann, W. F., (1996), Enhancing design for disassembly: a benchmark of DFD software tools, *Proceedings of the ASME DET and CIE Conference*.

2. Zussmann, E., Kriwet, A., and Seliger, G., (1994), Disassembly Oriented Assessment Methodology to Support Design for Recycling. *CIRP Annals*, 43(1), pp. 9-14.

3. Collen Mizuki, Peter A. Sandborn and Greg Pitts, (1996) "Design for environment – A survey of current practices and tools", *IEEE Transactions*, March, pp. 1-6.

4. Sanchoy K. Das and Sandeep Naik, (2002) "Process planning for product disassembly", *International Journal of Production Research.*

5. Kroll, E.,(1996) Development of a disassembly evaluation tool, *Proceedings of the ASME DET and CIE Conference*.

6. Jovane, F., Alting, L., Armillotta, A., Eversheim, W., Feldmann, K., Seliger, G., and Roth N., (1993), A key issue in product life cycle: Disassembly, *CIRP Annals*, 42(2), pp. 651-658.

7. Das, S. K., Narendra, P. and Yedlarajiah, P., (2000) "An Approach For Estimating The End-Of-Life Product Disassembly Effort and Cost" *International Journal of Production Research,* Vol. 38(3), pp. 657-673.

8. Y. Pnueli and E. Zussman, (1997) "Evaluating the end-of-life value of a product and improving it by redesign", International Journal of Product Research, Vol. 35, No. 4 , pp. 921-942.

9. Pradeep Kumar Yedlarajaiah, "Metrics for Estimating the Product Disassembly Effort", Master Thesis, New Jersey Institute of Technology, Newark NJ, 1999

10. Brennan, L., Gupta S. M., Taleb K. N., (1994), "Operations planning issues in an assembly/disassembly environment", *International Journal of Operation Production Management,* Vol. 14(9), pp. 57-67.

11. Kuo, T. C., (1999), Disassembly sequence and cost analysis for electromechanical products, *Robotics and Computer Integrated Manufacturing,* 16, pp. 43-45.

12. Sarat Chandra Gurram, "An automatic procedure generation of process plans", Masters thesis, New Jersey Institute of Technology, Newark, NJ, 2002