ABSTRACT

A DESIGN-FOR-RETIREMENT RATING MODEL FOR ENVIRONMENTALLY CONSCIOUS PRODUCTS

by
Xin He

Design-For-Retirement is a concept that allows one to design a product such that its retirement time and post-life treatment are optimized to lead to the minimum environmental impact and maximum financial gain. Retired product parts or subassemblies face three primary multi-lifecycle engineering treatments. The first one is to recondition them for reuse in the next lifecycle. The second one is to convert their post life parts into a material form for recycling back into new parts. The last is to dump or landfill them. Each option has a significantly different environmental cost-benefit ratio. Another important concern is the dismantling process of a product, which disassembles a product into subassemblies (clumps) and/or individual parts. It is not simply the inverse of an assembly process. The decision of a disassembly plan depends on which treatment results in the least environmental cost of each subassembly or part and maximum financial gain. The disassembly paths and termination goal may vary. This thesis focuses on building a combined optimization method of disassembly path generation and retirement planning regarding to the different recycle choices of parts or clumps. A matrix based representation method of product assembly information is presented. A method to rate a design in respect of its environmental effects in its post life recycle is also developed. They are demonstrated through several examples including two personal computer designs: conventional one and Compaq's design based on the Design-For-Retirement concept.

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by
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This thesis is dedicated to
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CHAPTER 1

INTRODUCTION

1.1 Product Design Concerns with DEF

Global environmental problems have clearly become a major issue in the recent years as industry moves into the 21st century. The need to diminish the environmental loads caused by human activities seems obvious to us. Today, both environmental concerns and rising product disposal costs are demanding for more environmentally friendly products. As a result of these economic restrictions, a firm's future competitiveness in markets depends upon making environmental issues a central concern.

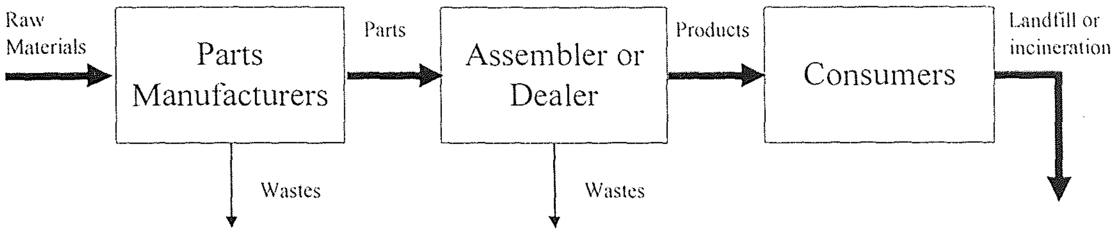


Fig 1.1 Product Life without Environmental Concern

The consideration of the environmental issues of the products requires designers to pay more attention to the design-for-environment (DFE) engineering aspect. Hence, designers have to take into account environmental impact along with many other product requirements from the design stage, the very beginning of a product life cycle. Figures 1.1 and 1.2 show two paradigms with and without taking the DFE concern into design. The paradigms in Figure 1.2 shows that the whole amount of wastes produced during the manufacturing, assembly and consumer usage of a certain product could be filtered before being dumped to environment. As the product recycling goes within a predesigned manner, raw materiel, energy and labor cost can be saved for the next life cycle, bringing further advantages to productivity and serviceability as the usable recycled parts join new products.

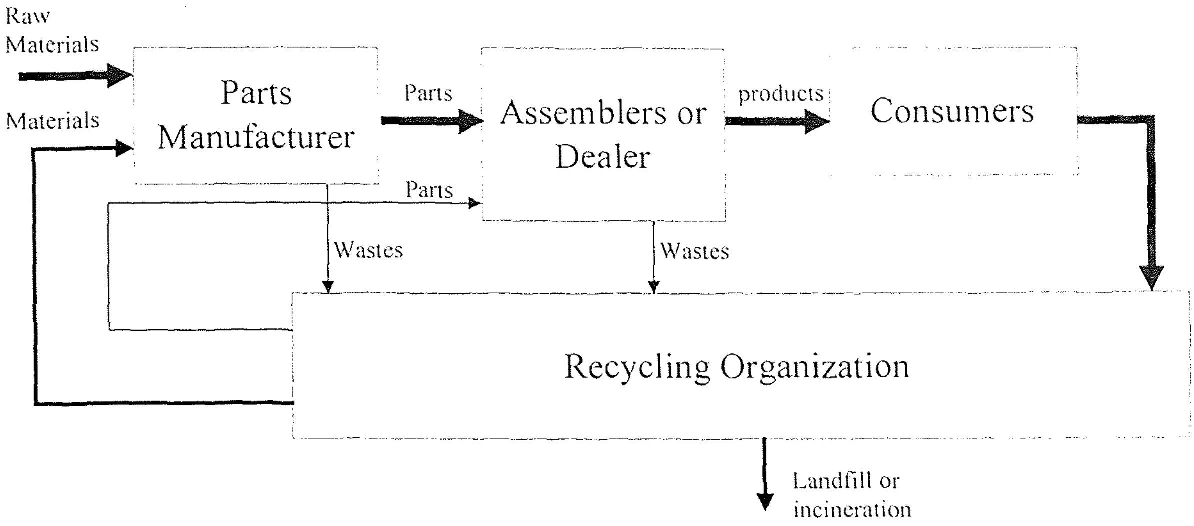


Fig 1.2 Product Life Cycle with Recycling Concern

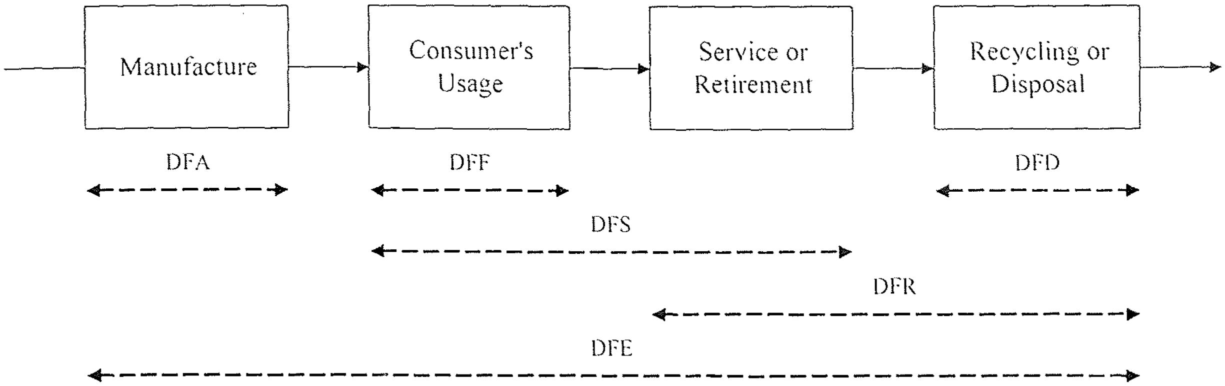
However, before any environmentally sound product can be developed, designers must have the understanding of the relationship between the environment and industrial products. To make any DFE concern practical to industry, designers need to make the usage of recycled materials and recyclable products economically profitable or at least tolerable. This will also increase the chances of a product being reused/recycled by taking DFE and recycle cost concern into the initial design. Because major part (about 70%) of all the cost of a product life-cycle is decided at the design stage, early-stage integration of the environmental consideration for future recycle-compatibility into design is a reasonable solution.

In the design stage of a product with specifically desired functions, a designer is responsible to incorporate various product life-cycle costs together. This thesis addresses the entire life-cycle usability of a product, including the aspects like primary functions, manufacturing and assembly cost, and serviceability. The focus is on the cost for reusing or recycling of a product.

1.2 Design for Retirement

Design engineers have control over many aspects of a product. One thing every design engineer must face is what will be the intended treatment for a product after it completes a life cycle. Whether designers intend to have the product discarded for landfill, or plan to reuse or remanufacture parts or all of the product will make significant difference in the environmental impact, cost for post life-cycle recovery, and even the industrial manufacturing pattern. In fact, some kinds of products from technologically advance industries like computer and communication industries have the trend to be out-of-date faster even though they still function well, and thus to be quickly discarded into a recycling organization. Design For Retirement (DFR) is especially important in these areas to keep the future environmental and industrial recycling burden low and consumers satisfied with relatively new technologies. To achieve all these goals we need to considerate many design aspects of a product, like Design for Function (DFF), Serviceability (DFS), Assembly (DFA), etc. In this thesis work, we focus our concern on the post life-cycle treatment of a product.

All of these aspects will take effect within a certain area of the whole life cycle of a product. And some of them have close relationships to one or more other aspects. To achieve a good post life retirement plan, we must take Design For Disassembly (DFD), Design For Environment (DFE) and Design For Serviceability (DFS) engineering aspects together into concern (Fig 1.3).



DFA: Design for Assembly
DFF: Design for Functionality
DFR: Design for Retirement
DFD: Design for Disassembly
DFS: Design for Serviceability
DFE: Design for Environment

Fig 1.3 The Effective Ranges of Different Design Aspects

Retirement is not just recycling. It takes a combined consideration of manufacturing labor, market pattern for specified products and environmental impact. A product with Designed-for-Retirement should satisfy, when retired:

1. It could be easily inspected and taken into large "clumps", a group of parts forming certain functionality, which is related to DFS and DFD;
2. Reusable parts could be easily taken off the assembly and reconditioned with the minimum cost, which is related to DFD and DFE, and;
3. Valuable rare materials could be isolated and recycled. Environmental damaging materials could also be kept within control.

Finding a method to reconcile these concerns and give a rating index for a specified design from the post retirement treatment aspect is the central work of this thesis. To achieve this goal, we need to have a disassembly analysis tool, and optimal disassembly sequence generator for clumps/parts with regard to disassembly cost of the clumps or part assembled. Then we can build a rating model based on the above two utilities.

1.3 Product Life Cycle Costs

In today's industry a product life cycle is viewed as the whole circle starting from manufacturing of raw materials and back to this point, including manufacturing, transport and dealership, consumer usage, recycle processing, remanufacture or landfill or incineration. Each of these stages brings considerable cost, and the whole process forms a closed loop with the environment providing material and energy as input and receiving industrial wastes as output support.

After a post life-cycle product being taken off duty, all the "clumps"/parts will be chosen for different fates regarding their original design intention for the post life recycle, their serviceability condition for reuse, and the market and environmental impact penalty at the time. To make the question simple, in this thesis we assume that all the "background" costs like market cost varying of parts and landfill penalty will remain the same within the product life cycles under consideration.

Many products are put into recycle far younger than their normal functional age because customers usually look for the latest and best features in their categories. They have a pattern of fast life cycles. Therefore some valuable parts in a product should be designed to put in use for several lifetimes until the cost to remanufacture them exceeds the cost of new parts. The algorithms [Zhang & Yu, 1997] have been developed to help decide the selection of material type and how many life cycles for a part to hold on in use to obtain the optimized cost-environmental result from information of landfill cost, new part cost, remanufacture cost and material value.

1.4 Retirement Optimization

Retirement optimization is to achieve a combined best result of environmental friendliness, recycle compatibility and industrial economic without compromising a product's quality or its commercial viability. The main elements we should take into consideration are:

- Which clumps or parts within a product have the best market recycling value, and what's the designed recycling intention for each clump/part (are they designed with intention to be reused, remanufactured, and recycled as raw materials, landfill or incinerated)?
- Which parts or clumps must be taken special attention due to environmental damage effect they might cause?
- How the clumps are assembled, and what is the disassembly sequence with minimum expense? All the clumps/parts need special attention must be taken out, and clumps/parts intended to be discard or reused should be taken suitable care;

We also need to balance weighting between disassembly difficulties/costs and material/market value to make the cost as low as possible.

With the retirement plan being optimized, the product future after its functional life will be known. Intended-for-reusing clump or parts may go much shorter loops and back into a product life cycle until the remanufacture expense exceeds the benefit of reusing them. The recycle burden could be distributed among dealer/assembler, manufacturer and recycling organization. The recycling model could be changed to the one in Fig 1.4.

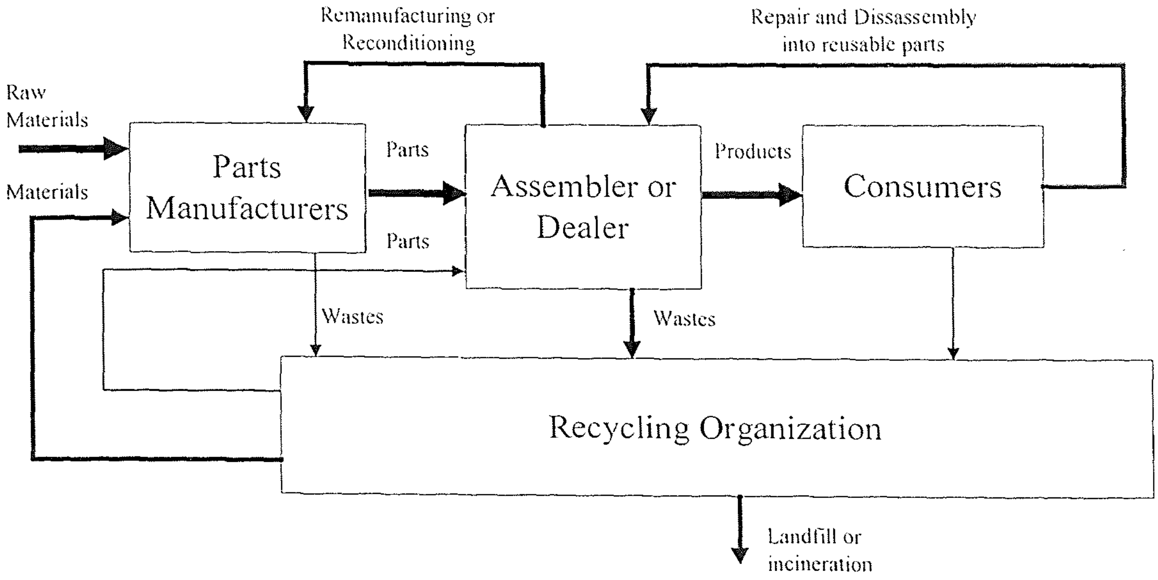


Fig 1.4 Product Life Model with Design for Retirement Optimization

CHAPTER 2

ELEMENTS OF ENVIRONMENTALLY CONSCIOUS DESIGN

2.1 Material Usage with Environmental Concern

Choosing raw materials for certain component or components within a product is the first step that affects the product's lifecycle cost and environmental impact analysis. A product may have many different input and output cost patterns depending on the analysis viewpoints and which environmental, engineering or market aspects are emphasized in the analysis. We may have input information about raw material cost, engineering and manufacturing cost, assembly cost, market circulation cost, lifetime maintenance cost, and post-life recycle cost. The outputs may include financial benefits, waste cost during manufacturing, waste cost during assembly/disassembly, and whole lifecycle benefit gain. In the product life cycle environmental concern model shown in Chapter 1, raw material factor is the only input we take into consideration throughout the whole lifecycle.

When a whole product is considered, many aspects need to be considered. An example is the material complexity problem introduced by the whole product environmental effects during assembly/disassembly in choosing the material of components. Choosing different material for parts also changes the overall product environmental effect and the time for product retirement. Generally, the material recycle of a product component can be considered within two groups:

- Closed-loop recycle, in which components, subassemblies and material go back into a new product in the same class;

- Open-loop recycle, in which material goes into lower level of recycle for degraded class of products or landfill.

Closed-loop recycle is the process of reintroducing recycled material into the process of manufacturing of new products in form of either remanufactured product parts or recycled material. In this group, the material will be put in use in more than one product lifecycles in some form. This is a form called "material mortgage". The material falling into this group is generally of high value, since the recycle process will bring back the "mortgaged" high value material for reuse in several lifetimes, thus the overall product cost or price will be kept within a reasonable range. This process will need the components made of the specified material to be designed to bring minimum cost in a recycling and reprocessing procedure.

Open-loop recycle is the process of discarding the material out of the industry when the lifecycle is completed. Here "discarding" means the material of post lifecycle product will not be reused either as remanufactured components or direct material for manufacturing of the components of this product. The material will be put into a lower level of recycling circle than the product under consideration or put into landfill. In this process if the material is designed to be discard, it should be of minimum possible value and result in the lowest landfill or other environmental effects.

Another influence of material choices upon the overall product environmental effect is the material complexity problem. Material complexity is also decided at the design stage, and has an important role in determining the recycle decision plan and total recycle cost of a product. Here material complexity is mainly affected by the number of kinds of materials used in the components and/or subassemblies of a certain product. It, however, may depend upon the recycling technology that reflects the ability to process some or all materials of a product. In detail, material complexity is a function of the following factors:

- Number of material types used, which strongly influences the recycle cost of a product;
- Number of material types requiring special care. Most "mortgaged" material requires special care and handling to make its remanufacture cost the minimum;
- Material compatibility, which requires incompatible materials used by product parts to be processed separately with the minimum cost. This is partially determined based on the current recycling technology.

2.2 Engineering Environmental Concern

The next major environmental concern of a product is its engineering process. It includes:

- Manufacture from material into components;
- Assembly of parts into a product;
- Disassembly process if the product needs to be disassembled into parts for recycle after one product lifetime;
- Material processing which processes the used parts containing reusable material into the recycled material for the next life cycle.

- Reconditioning used parts such that they are directly useable for the nest lifecycle.

These engineering processes can be illustrated in a circular form in Figure 2.1 with raw material as the input from environment and various discarding options as outputs to the environment.

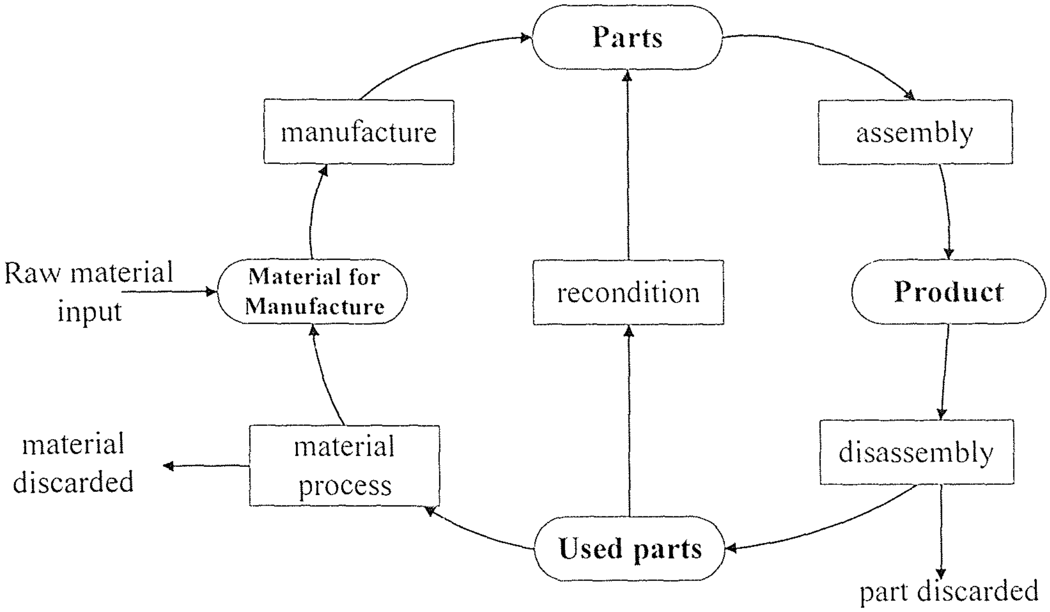


Figure 2.1 Engineering Process Circle

To consider the engineering environmental effect, the following information should be obtained:

- Assembly and recycling technologies used;
- When should the product be put into retirement;
- The intended post lifetime fate of functional clumps decided during the design stage and the disassemblability of each clump depending on its fate.

More detailed analysis methods like the one in [Lee and Ishii, 1997] use the concept of Sort Complexity to sort the recycle treatment of products, into several levels with different processing technology. The Sort Complexity concept captures more detailed characteristics of a recycling process and can assist the recycling organization in planning Design For Environment (DFE) product in relation with the recycling technology and components reuse policy. The sort complexity is thus a function of disassembly and clump processing.

2.3 Total Product Life-cycle Environmental Effect

From Sections 2.1 and 2.2, we can see that the concern ranges of material usage and engineering processes have overlapped each other in some extend. In practice, these concerns do not take effect separately. The total environmental effect of a dynamic lifecycle of a product is the combined result of all the concerns.

In the Design-For-Retirement consideration, the disassembly cost should be kept minimum, and the components or clumps made of closed-loop recycle material should be easy to disassemble from the rest of an assembly. The usage of higher value closed-loop material will give higher recycle ratio thus save the energy used and the landfill penalty, but requires high initial material expense and may cost more in reprocessing and reconditioning. While the usage of more open-loop material will reduce initial material cost and the recycling cost but may cause a higher price for the landfill environmental effect. In order to derive the maximum benefit gain, we should optimally select the usage of closed-loop and open-loop materials for a particular product.

In the engineering aspect, component parts made of closed-loop kind material generally should be designed to provide easy access to them and with lower disassembly cost. The trade-off should be sought for a product in terms of less engineering complexity, less recycling Sort Complexity, and lower disassembly cost.

CHAPTER 3

DISASSEMBLY SEQUENCE PLANNING

3.1 Assembly Sequence Planning

Assembly sequence planning is the opposite of disassembly sequence planning. It is a high-level plan for constructing a product from component parts. It specifies which sets of components form subassemblies/clumps, the order in which components and clumps are to be assembled into the product. The main objective of assembly planning analysis is to determine the sequence of assembling a product with respect to its geometric and resource constraints. Assembly and disassembly sequence planning shares many common characters and similar engineering goals. Similar models and methods are often used to derive these plans. While this thesis work focuses upon the disassembly and retirement plan optimization of a product, it is important to study the assembly planning analysis.

In all the assembly/disassembly planning analysis, we make the following major assumptions of the components and assembly/disassembly process:

- All components have solid connection points, and will not change shape during assembly or disassembly unless intended to be broken;
- The components or clumps are assembled to their final positions in the product assembly or removed from this assembly in one translation;
- In assembly, once a component or clump is placed, it will not be moved;
- Once clumps are formed, they are assumed to be stable as a whole unit during an assembly or disassembly process;

- There are no internal forces in the assembly to hold the components/clumps in places except the connection point between each other.

The engineering goals of assembly/disassembly sequence planning analysis are both to make minimum engineering process cost for the whole life cycle of a product. They become an essential part of the engineering design exploration process.

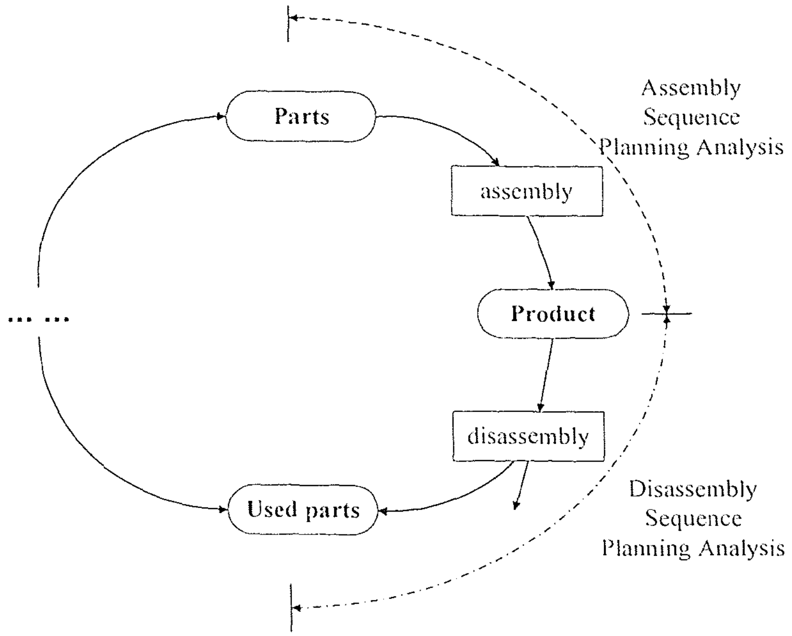


Figure 3.1 Assembly and Disassembly Analysis Coverage of the Engineering Circle

In the viewpoint of Design-For-Retirement practice, assembly sequence planning is a part of Design-For-Assembly, which is the process and set of design guidelines for improving product designs for easier and lower cost assembly. Its goal is to deliver a cost-effective assembly plan. Disassembly sequence analysis, in the mean time, has more relationship with the material complexity and disassembly treatment complexity problems. The assembly and disassembly analysis coverage of the engineering process circle is illustrated in Figure 3.1.

3.2 Disassembly Sequence Planning

3.2.1 Problems of Disassembly Planning

This section discusses several major problems of generating and representing disassembly plan in detail. To generate optimized disassembly plans, there are definitional and computational problems. The first problem of choosing the best plan arises from the range and complexity of the issue that must be considered: the complexity of fixtures, the degree of parallelism permitted, the number of subassemblies and the difficulty or technology required in the disassembly operations.

The second problem that faces disassembly sequence planers is the computational workload. For a given product or a subassembly, after sorting out the disassembly levels and paths, the number of possible plans for even some simple exemplary assemblies may be fairly large [Wolter, 1991]. It is often difficult to give a good disassembly level and path searching result for a much more complex and realistic product. The running time of optimization algorithms typically grows in exponential time. [Chakarbarty and Wolter, 1997] gives a new approach with significant advances in the ability to specify complex, realistic criteria and to find good plans rapidly according to those criteria. This approach is based on viewing an assembly as the hierarchical collection of standard structures. The procedure of generating an optimized disassembly plan is described in the following paragraphs.

First, the geometric information is captured in symbolic constraint languages that represented assembly information in a mathematical form. As the parts are being disassembled, a valid disassembly plan must ensure that no intersections occur between them. That means the parts should be disassembled in a linear or parallel manner. Two major forms of constraints languages are used:

- Insertion constraint languages, describing constraints on which parts block removal trajectories of other parts, and;
- Mating constraint languages, describing constraints of the order in which pairs of parts can depart.

In this thesis, a combined matrix form assembly information representation method is developed as described later in Chapters 5 and 6.

Next, the structure of an assembly under consideration is analyzed. Existing structure library containing information about preferred ways to disassemble common assemblies is used to make complicated product structure analysis easier and faster. Some structures may contain other substructures. Thus the assembly structures may be arranged into a hierarchy with the large, high-level assembly containing smaller subassemblies. Such assembly hierarchies may not be unique. Different ways of dividing and disassembling an assembly may be motivated by different views of the product assembly. It is important to make note that the structure hierarchy does not give a geometric description of the assembly, and is not intended as a substitute for a geometric model. It only describes a symbolic structure of the assembly, grouping together elements that have some significant relationships to the function or manufacture of the assembly.

To produce correct plans, additional geometric information is required in the form of knowledge about which part motions intersect with other parts. Assembly structures can be classified by type. Because many structures appear repeatedly in a wide variety of assemblies, descriptions of such common structures and description of its substructures can be stored in some sort of library. With the use of a well-stocked structure library, although the complete structure hierarchy for a given assembly may be very large, to generate this hierarchy will not be so burdensome because subassembly information can be derived from the library.

A disassembly planner should not make decisions in any fixed temporal sequence, but plans top-down in the structure hierarchy. First, plans are generated for the highest-level assembly structures, and then disassembly plans for subassembly/clump can be built regarding to the requirements of further disassembly of substructures. It seems a more natural order to work on only those subassemblies that have been decided for further disassembly by a higher-level disassembly plan. This can lead to new plans that can be viewed as simultaneous or sequential executions of the sub-plans to form an overall product disassembly plan.

Finally, after the disassembly plans are generated for a product, the problem is the representation of plans. The plans can be given at different levels of abstraction. The greater the details provided, the less abstractive the plan is. Disassembly plan representation generally provides only a partial description of the assembly task and thus many possible disassembly processes can be considered valid executions of that plan. It is then critical to decide what detail should be included in the plan and which process should be used at disassembly planning and execution stages. If too little details are included in the plans, they become difficult to evaluate. If too much details are included in the plans, then the planning process may become slow because many plans that are essentially equivalent may be treated as different ones by the planner. Therefore, it is important to try to define plans at an abstraction level which is detailed enough so that the quality of the plans can be kept with respect to a certain set of criteria, but not so detailed as to avoid a slow planning procedure. An example of the structured approach to the assembly sequence planning is given in [Chakarbarty and Wolter, 1997].

3.2.2 A Graph-Based Disassembly Representation Model

Disassembly Petri nets are proposed by Zussman and Zhou (1997) to model and adaptively plan disassembly processes. Detailed alogrithms are presented and applied to an AT&T telephone.

The disassembly model in general needs to accommodate both geometric and nongeometric information. In this subsection, we give a brief review of a graph-based disassembly representation model based on the work by [Swaminathan and Barber, 1996]. They discuss an example of the geometrical information of an assembly that can be graphically contained in three graphs. We use floor lamp assembly shown in Figure 3.2 to illustrate the model in the work of [Swaminathan and Barber, 1996]. Its three corresponding geometrical information graphs are shown in Figure 3.3.

1) The connections graph in Figure 3.3 (A). This is a graph that identifies all the connections between parts. It is an undirected graph with labeled edges indicating the type of connection made by that edge.

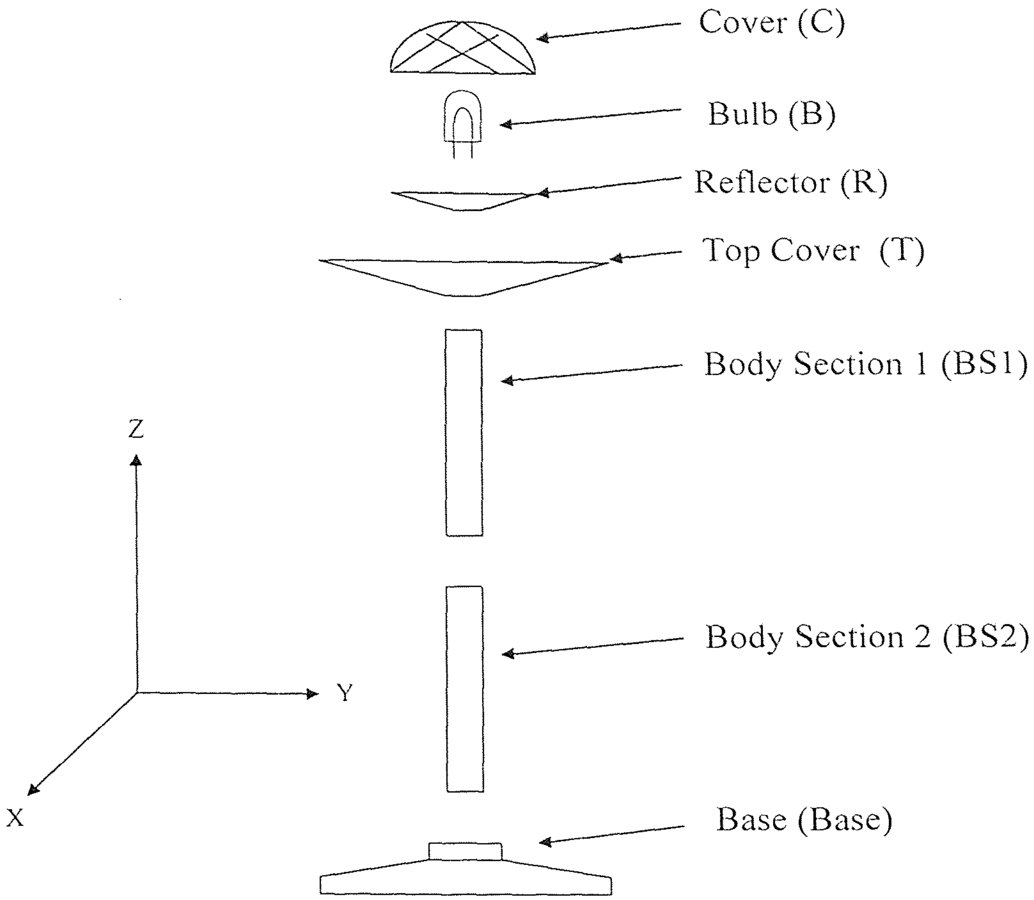


Figure 3.2 Floor Lamp Example for the Graph-Based Model

2) The mating directions graph in Figure 3.3 (B). This graph identifies the directions that are available for each part to connect with its mating parts. Each directed arc is labeled with the direction in which the source node can mate with the destination node. The arcs emerging from a node indicate all its mating directions. All the arcs ending in a node show the directions in which other parts can connect to it.

3) The obstacle facts graph in Figure 3.3 (C). This graph represents the list of blocking parts that prevent the mating of other parts along certain mating directions if the blocking part is placed earlier in the sequence than the other part. This is also a directed graph. The source node denotes the blocking part and each of the arcs ends in the part that is blocked. The direction which is blocked is indicated as a label on the arc.

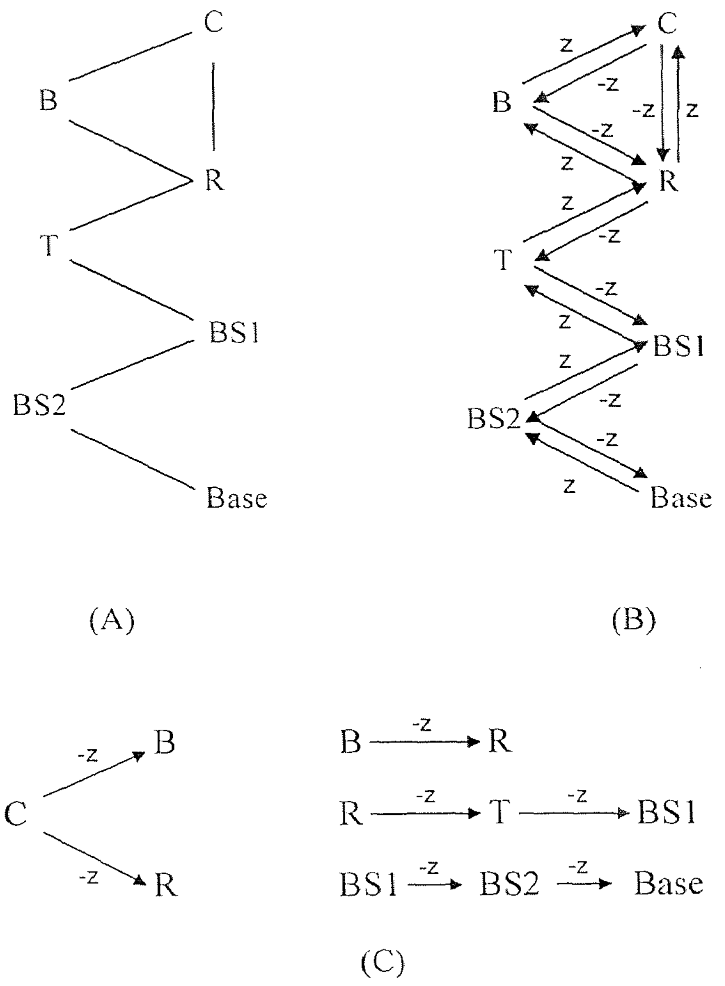


Figure 3.3 Graphs of Example in Figure 3.2

3.3 Design-for-Disassembly and Design-for-Retirement

In the previous sections of this chapter we have reviewed the problems and procedures toward generating a disassembly plan. These disassemblability analyses play an important role in the Design For Disassembly engineering aspect. In this thesis, we mainly focus on the environmental effects caused during the whole product life cycle, which includes the concerns from material usage to engineering cost. Design For Retirement, which is the central topic in this work, combines the analysis of engineering process effects and the engineering-environment treatment. Generally speaking, Design-For-Disassembly concerns about the sequence and cost of disassembling parts from product assembly. While Design-For-Retirement is concerning more with the environmental and marketing effects of products, trying to find solutions in engineering design for the optimized cost-benefit effect with regard to all the engineering elements that take effects. In the next chapter, we will give a review of the product part lifetime cost analysis.

CHAPTER 4

PRODUCT PART LIFECYCLE COST

Before the retirement optimization is discussed, the lifecycle costs of individual component unit (part or subassembly) of a product need to be discussed in detail. This chapter, a review of different part lifecycle costs and their relationships, and analysis the optimization method to choose the appropriate parts according to their lifecycle costs.

4.1 Various Parts Lifecycle Costs

Many aspects of a part affect its lifetime and environmental features during its lifecycle. As discussed in Chapter 1, a part's lifetime may expand one or several product lifetimes regarding to the recycling model of this part. A recycled part reenters the new product life circle in various forms like remanufactured part, high-level recycled material or low-level recycled material (Chapter 2). Retirement optimization means obtaining the highest benefit value by making right decisions about whether to recycle a part, when and how to recycle it after each lifecycle. To choose a part's retirement plan optimally, we consider several characters of its lifecycle. Each lifecycle changes the engineering character, reuse value and recycling cost of a part to some degree. This shows that retirement optimization is a dynamic problem. It should be performed after each lifecycle to calculate the result of benefit and penalty to see in which method a part should be recycled or whether it should be recycled at all, according to its characteristic values. Parts selection is also an important aspect of Design-For-Retirement concern. [Zhou, et al., 1996] has defined a set of cost criteria to help the analysis of part selection optimization. This set of criteria also aids the retirement decision making process.

The goal of our analysis is to minimize the overall net environmental impact brought by a product life cycle. For every recycled individual unit (part or subassembly) there are three primary treatments: reconditioning and reuse in a functional form, material reuse, and landfill. Each treatment has its corresponding environmental impact represented as cost. Following paragraphs discuss the cost related with these treatments in detail.

The first major concern when dealing with a recycle unit for reuse is its engineering condition. This is judged by the unit's possibility being good and failing after one lifecycle, P_{good} and $P_{failure}$, with relative remanufacture cost of C_{good} and $C_{failure}$ to recover the part for reuse in the next lifecycle. We can safely assume that C_{good} is much lower than $C_{failure}$. For products with a high out-of-date rate, the whole remanufacture cost should also reflect the loss caused by aging, $C_{out\text{-}of\text{-}date}$. Thus the entire expense to remanufacture and reuse a retired unit is then:

$$C_{total} = C_{good} * P_{good} + C_{failure} * P_{failure} + C_{out\text{-}of\text{-}date}$$

The probability of failure of a post life unit can be expressed by exponential factor: $P_{good} = e^{-\lambda t}$, here λ represents the degradation rate of the part, and t represents the time in service. And the cost to take a recycle unit from the assembly should also be added, thus the final cost of unit remanufacture and reuse individual unit can be expressed as:

$$C_{total} = C_{good} * e^{-\lambda t} + C_{failure} * \left(1 - e^{-\lambda t}\right) + C_{out-of-date} + C_{disassembly}$$

The other two kinds of treatments bring material processing cost $C_{material\ process}$ and landfill cost $C_{disposal}$. These costs are relatively simple compared with the remanufacture cost, and usually have fixed value. The final cost of each treatment is a relationship equation of these above costs. The material recycle cost of a clump or part is the total of disassembly cost and material processing cost. The landfill cost is the total of $C_{disposal}$ and disassembly cost. The cost, benefit and final gain of each treatment are discussed in chapter 6.

The three treatments may result in different disassembly costs. The analysis of disassembly cost and disassembly sequence planning is the central topic of the next chapter.

4.2 DFR Optimization within a Product

The optimization of part retirement planning is a problem that should be considered within the whole assembly process. A product's assembly layout can be represented by an upside-down tree structure similar to the work of [Zhou, et al, 1997]. The whole product is the root of the tree, and subassemblies and parts form the lower levels of the tree, as illustrated in Figure 4.1. Each node represents either product assembly, subassembly or individual part.

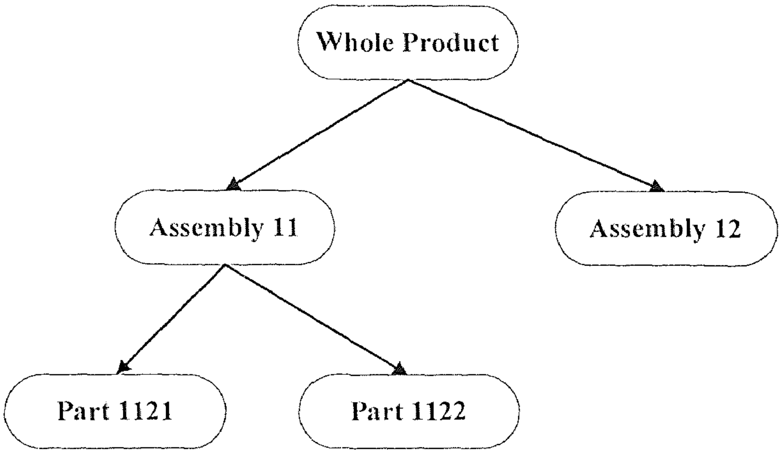


Figure 4.1 Product Assembly Tree Structure

Each one of the nodes in the product structure tree has four major retirement choices. The first three ones are reusing, material recycle and landfill as we discussed in Section 4.1, the last one is to disassembled the node into the next level of subassemblies or parts (nodes). For every node, the treatment with the minimum cost hence brings the least environmental impact should be chosen. The costs of each treatment are:

- Remanufacture, $Cost = C_{\text{disassembly}} + C_{\text{remanufacture}}$
- Material recycle, $Cost = C_{\text{disassembly}} + C_{\text{material process}}$
- Landfill, $Cost = C_{\text{disassembly}} + C_{\text{disposal}}$
- Further disassembly, $Cost = C_{\text{disassembly}} + \sum Costs\ of\ lower\ levels$, where *costs of lower levels* are the costs to treat further lower-level nodes disassembled from the current node, each of which also has the above retirement choices.

The retirement optimization begins from the root (whole product). With the assistance of generated disassembly sequence (discussed in chapter 5), the retirement costs of every node in a product tree structure can be calculated and the further treatment can be chosen. If the first three treatments cause lower costs than the last option, the node is then called a stopping node which doesn't need to be disassembled and should be recycled as a whole clump. This analysis can also be performed by employing the concept of Gain, which equals the benefit minus the cost. This analysis requires product structure representation, disassembly sequence generation, cost/benefit calculation. Chapter 6 discusses this problem in more details.

CHAPTER 5

DISASSEMBLY OPTIMIZATION

5.1 A Design-for-Disassembly Framework

Disassembly sequence is defined as an order in which components in a product are disassembled. We define de-manufacturing as a process of disassembling a product into subassemblies and components and reusing, recycling or refurbishing them. Disassemblability refers to the degree of ease to remove a selected component from an assembly. Key elements affecting the disassembly work planning include:

- Whether to break a product into large functional-recycle groups (clumps) or break into individual parts;
- How the components in a product are assembled: welded, glued, riveted, screwed, clasped, etc.;
- Whether to take selective disassembles to extract functional clumps for remanufacture, which requires only a portion of an assembly to be disassembled, or to take a complete disassembly to get the valuable parts;
- The environmental impact caused during the disassembly, which requires us to take a disassembly plan that produces the least amount of waste.

We also need to note that the most economical assembly sequence needs not be the most economical disassembly sequence. Moreover, the differences between assembly and disassembly analysis make a separate study of product disassemblability essential. Several methods like [Dundee, 1994], [Srinivasan et al., 1997] and [Ishii et al., 1996] have already been developed to determine the disassemblability of a product's geometry and to generate its disassembly sequence.

As to [Srinivasan et al., 1997] there requires several steps to build the product disassembly tool: a) product analysis, b) disassemblability analysis and, c) disassemble sequence and direction optimization. Finally we can derive a design rating.

A Design-for-Retirement Geometric Framework is given in Fig 5.1.

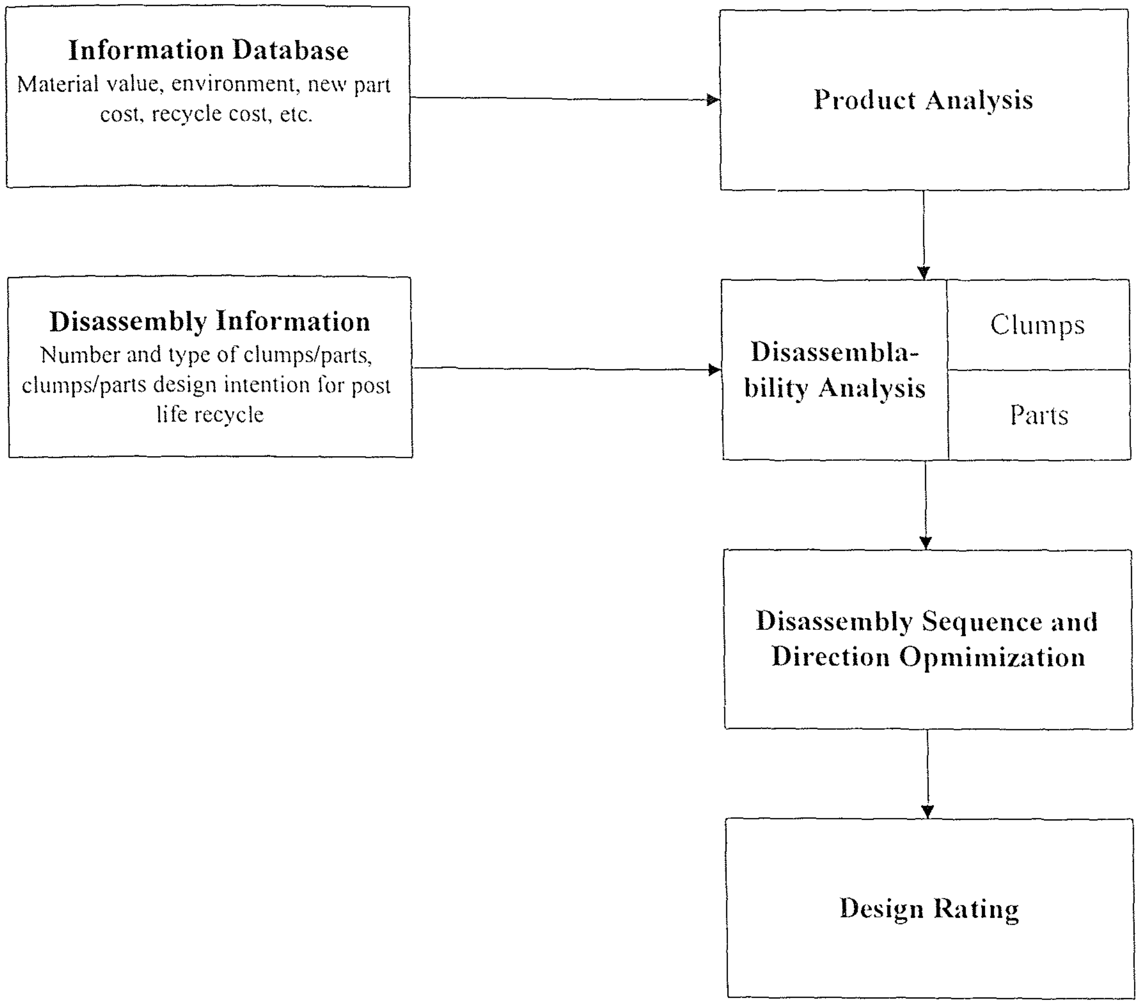


Fig 5.1 DFR Framework

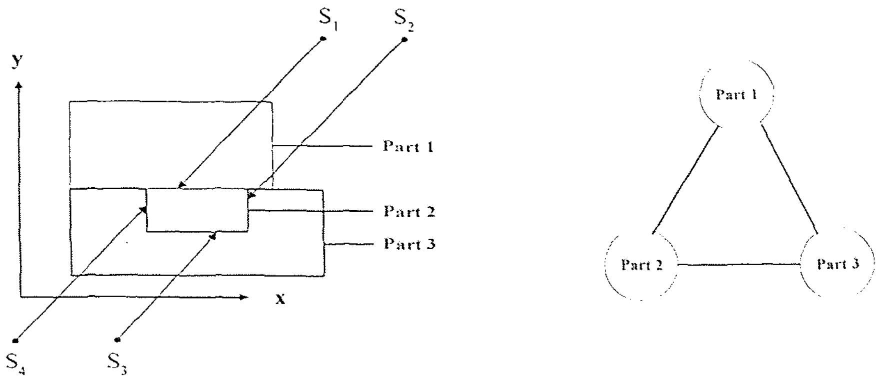
In detail, these steps involve:

1. Performing product analysis and selecting the components to be disassembled and an appropriate de-manufacturing plan;
2. Determining the disassemblability of components and analyzing the possible disassembly methods, and selecting an appropriate disassembly path that fits user requirements best;
3. Generating an optimal disassembly sequence and directions (if applicable) for the components/clumps to be disassembled;
4. Evaluating the design for parameters such as cost and time in disassembling the components/clumps, which allow designers to establish how well a product is designed regarding its post life cycle recycling performance.

The following discussions will focuses on the steps 2 and 3, disassemble sequence generation.

5.2 Disassemblability Analysis

Disassemblability analysis analyzes a retirement plan. A part/clump is disassemblable if it can be removed from the rest of the assembly. The geometrical information of a product's assembly such as mounting points and direction, is very important in this analysis.



(A) (B)

Fig 5.2 (A) An assembly Example and (B) The Connectivity Diagram

Fig 5.2 shows an assembly example [Srinivasan, et al., 1997] consisting of three components P_1, P_2, and P_3. They have four mounting surfaces S_1, S_2, S_3, and S_4. To make the analysis simple, we consider only 2-D direction disassembly map as shown in Fig 5.2. For a single component, find out all of its mounting surfaces. For example, part 2 in Fig 5.2 has mounting surfaces S_1, S_2, S_3, and S_4 contacting with P_1, P_3, P_3, and P_3 correspondingly. Now consider only surface S_1. It allows part 2 to be disassembled from any direction in the lower half sphere. Next for S_2, we see that part 2 can be removed from the left side sphere. Continue this process with all the surfaces part 2 has, we obtain the allowed disassemble direction for each mounting surface in Fig 5.3, The final resultant disassembly direction for part 2 will then be the intersection of all the separate directions we obtain from the mounting surfaces. It is NULL in the case of part two.

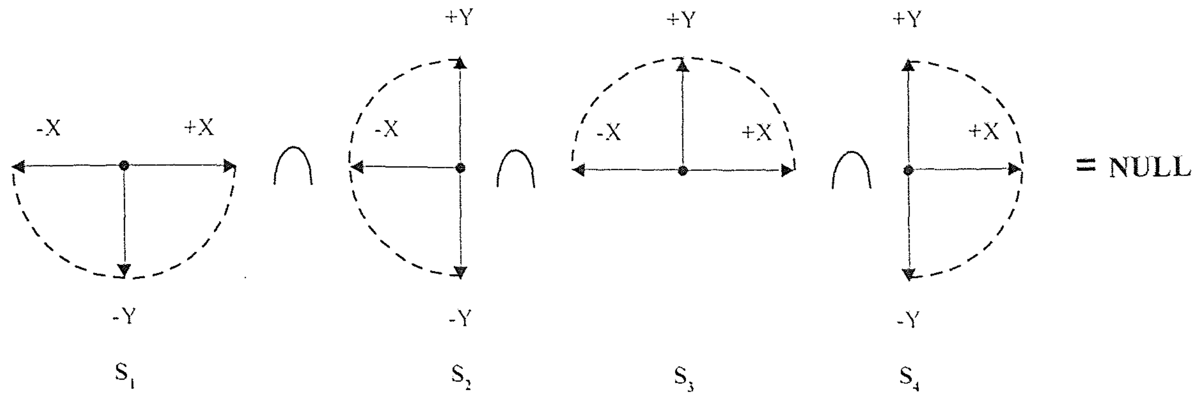


Fig 5.3 Disassemblability Analysis of Part 2 in Fig 5.2(A) [Srinivasan, et al., 1997]

If we find that the resultant intersection is NULL, the component is not disassemblable at this stage of disassembly. We should look for other components that can be disassembled at present. In any stage, there must be at least one component that can be removed. Go to the disassembly direction searching process for several stages and we will find out all the possible disassembly sequence of a product. By making similar analysis for part 3, we obtain Fig 5.4 and find out that part 3 is disassemblable from direction –Y, part 1 from $\pm X,+Y$. The disassembly path for this example is $[part1,\pm X,+Y;part3,-Y] \Rightarrow [part2]$

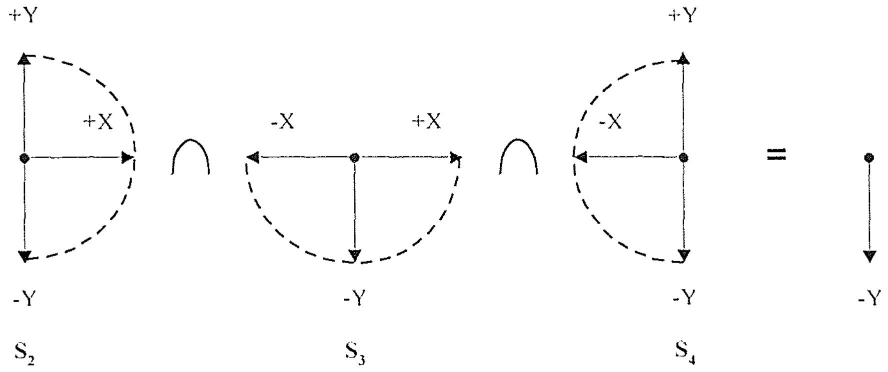


Fig 5.4 Disassemblability Analysis of Part 3 in Fig 5.2(A) [Srinivasan, et al., 1997]

5.3 Disassembly Information Representation

We have shown the disassembly information of a product in a form of the connection graph of nodes in Fig 5.2B as an example. Each node represents a part in Fig 5.2A. In most cases, in order to be more efficient, we do not need to disassemble the whole product into individual parts. A product is usually taken into functional clumps. For example, in most garages or junked yard, one takes a whole engine or transmission as a part for reuse. Individual parts seldom count in these instances. We emphasize the treatment of clumps instead of separate parts in them. Therefore, before a disassembly sequence analysis, we should mark the points needing attention within certain clumps like rare raw materials used which must be taken back in recycling, and poisonous containing which should be recycled with proper care. Only these clumps need to be taken for further disassembly since the overall recycling cost may be high if they are treated as a whole. Thus the nodes of a disassembly information graph should represent only the functional clumps at the first level, then the clumps having further interest should be broken into the second or deeper level of disassembly. This will save analysis time to reduce the burden. The cost optimization for disassembly will be discussed in detail in the next chapter.

To ease retrieving data for building a disassembly analysis tool, it is necessary to translate the nodes connection graph into a mathematical representation. We use a Node Information Matrix (NIM) to describe the information of both nodes and their connections.

$$A_{NIM} = \begin{bmatrix} N_1 & 0 & \cdots & \cdots & 0 \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ E_{i1} & \cdots & N_i & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & 0 \\ E_{n1} & \cdots & E_{ni} & \cdots & N_n \end{bmatrix}$$

Here $N_i (i = 1 \ldots n)$ represents the information structure of the *ith* node, E_{ij} $(i=1 \ldots n,$ $j=1 \ldots n,$ $i \neq j)$ represents the connection relationship information structure between the *ith* and *jth* node.

$$E_{ij} = \begin{cases} 1, & N_i \text{ and } N_j \text{ are connected} \\ 0, & \text{Otherwise} \end{cases}$$

However, to make the detailed analysis of disassembly, we need to construct a structure containing more information. Here the node information structure contains:

- Node ID //the index number of the node
- Node Name //name of node
- Material value //rare, rare material coated, valuable, common, discardable
- New part cost //cost to buy a new part/clump for replacement
- Remanufacture cost //cost to recondition used clumps/parts to usable state
- Material Recycle cost //cost to recycle clumps/parts to raw material
- Disposal cost //cost to landfill or incinerate the component
- Out-of-date rate α //reuse value $= OriginalValue * e^{-\alpha t}$
- Part age //the age of part is important for recycling of high out- //of-date rate products that are often technologically // advance
- Degradation rate λ //reconditioning cost $= e^{\lambda t}$

The connection information structure contains:

• Link state	$//\begin{cases} 1 \ \mathit{linked} \\ 0 \ \mathit{unlinked} \end{cases}$
• Interference mode	//the connection information for the node in directions //+X,-X,+Y,-Y,+Z, and -Z
• Points of connection	//the number and type of point connection in X,Y, and //Z directions

5.4 Disassembly Sequence Generation

Once we decide the nodes (clumps in the 1st level and individual parts in the 2nd level), and build the Node Information Matrix, we can analyze the disassembly sequence planning in detail.

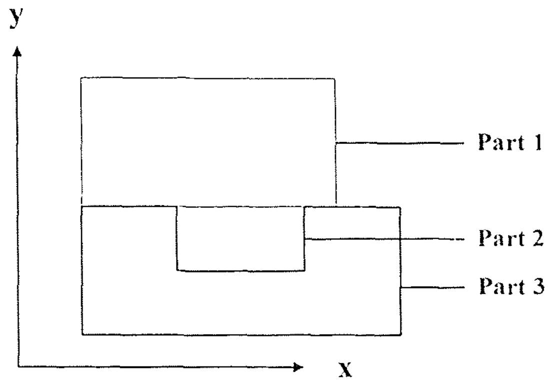


Fig 5.5 Disassembly Sequence Analysis Example

Consider the simple assembly in Fig 5.5, We can build the following Disassembly Direction Matrix (DDM):

$$A_{DDM} = \begin{bmatrix} N_1 & 0 & 0 \\ I_{21} & N_2 & 0 \\ I_{31} & I_{32} & N_3 \end{bmatrix} = \begin{bmatrix} N_1 & 0 & 0 \\ -Y & N_2 & 0 \\ -Y & \pm X, -Y & N_3 \end{bmatrix}$$

Where:

N_i represents the *ith* node, I_{ij} represents the interference mode between the *ith* and *jth* node. Starting from N_i, and going along the column down, I_{ji} show the directions in which N_i is connected to other nodes, going along the row to the left, and I_{ij} shows the directions in which other nodes are connected to N_i oppositely. To obtain the allowed disassembly directions for N_i, we denote D as the set of all directions, which is $\{\pm X, \pm Y\}$ for the 2-dimension case and $\{\pm X, \pm Y, \pm Z$ for the 3-dimension case. Given A_{DDM}, the disassemble direction of N_i can then be derived by the following formula:

$$D_i = D - \left\{ \left[\bigcup_{i<j} \{ I_{ji} \} \right] \cup \left[\bigcup_{i>j} \{ -I_{ij} \} \right] \right\}$$

Given the example assembly in Fig 5.5 and its A_{DDM} matrix, we could find the disassembly directions for each part:

N_1: Disassembly Direction: $\pm X, +Y$;

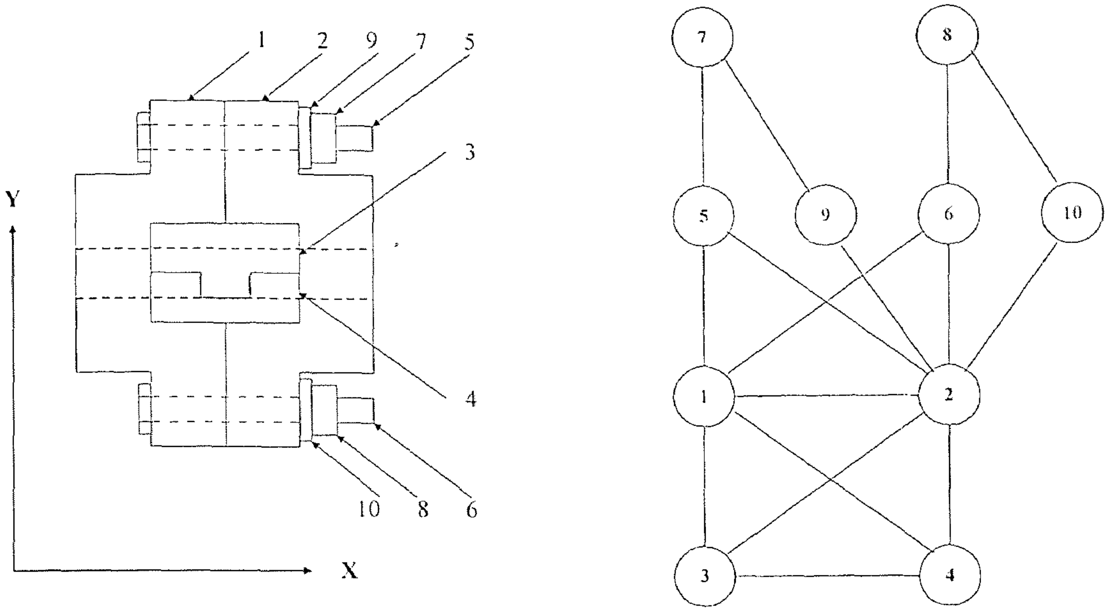
N_2: Disassembly Direction: *NULL*;

N_3: Disassembly Direction: -*Y*

We see in step 1 that only N_1 and N_3 can be removed. N_2 can be removed in step 2 after N_1 and N_3 have been removed. The disassembly sequence can then be built as follows:

$$\begin{bmatrix} N_1 & 0 & 0 \\ -Y & N_2 & 0 \\ -Y & \pm X, -Y & N_3 \end{bmatrix} \Rightarrow \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \end{bmatrix} = \begin{bmatrix} \pm X, +Y & NULL & -Y \\ \backslash & \pm X, \pm Y & \backslash \end{bmatrix} \Rightarrow \{(N_1, N_3), N_2\}$$

Where S_{ji} represents the directions in which N_i can be disassembled in step j, $1 \le i \le 3$, and $1 \le j \le 2$. To explain the usefulness of a Disassembly Direction Matrix, let us consider a more complex example in Fig 5.6A.



(A)

(B)

Fig 5.6 An Assembly Example

We choose each individual part as a node. The example assembly can only be disassembled into individual parts which are the terminal nodes in this example. Complicated products made of many functional clumps will need several levels of similar analysis. First consider all the clumps as nodes, and then individual parts within certain clumps as nodes when necessary until the optimized retirement cost has been achieved. Once the nodes have been decided, the assembly can be represented by connectivity diagram in Fig 5.6B, where we consider individual components as the nodes.

Consider only the 2-D direction disassembly, and use equation $E_{ij} = \begin{cases} 1, & \mathit{linked} \\ 0, & \mathit{unlinked} \end{cases}$ to represent the component connection status. The Node Information Matrix (NIM) of this assembly could be built. Further analysis combining the cost optimization of disassembly and environmental impact could also retrieve their data from this matrix.

$$A_{NIM} = \begin{bmatrix} N_1 & 0 & & \cdots & & \cdots & & \cdots & & 0 \\ 1 & N_2 & & & & & & & & \\ 1 & 1 & N_3 & & & \cdots & & \cdots & & \cdots \\ 1 & 1 & 1 & N_4 & & & & & & \\ 1 & 1 & 0 & 0 & N_5 & & & \cdots & & \cdots \\ 1 & 1 & 0 & 0 & 0 & N_6 & & & & \\ 0 & 0 & 0 & 0 & 1 & 0 & N_7 & & & \cdots \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & N_8 & & \\ 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & N_9 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & N_{10} \end{bmatrix}$$

Then we can build the Disassembly Direction Matrix (DDM) with regard to the interference direction blocking of the components to each other. Note that every checked element (the “1” s) in matrix A_{NIM} has the corresponding entry in A_{DDM} :

$$A_{DDM} = \begin{bmatrix} N_1 & 0 & & \cdots & & \cdots & & \cdots & & 0 \\ +X & N_2 & & & & & & & & \\ +X,\pm Y & -X,\pm Y & N_3 & & & \cdots & & \cdots & & \cdots \\ +X,\pm Y & -X,\pm Y & \pm X,-Y & N_4 & & & & & & \\ -X & \pm Y & 0 & 0 & N_5 & & & \cdots & & \cdots \\ -X & \pm Y & 0 & 0 & 0 & N_6 & & & & \\ 0 & 0 & 0 & 0 & \pm Y & 0 & N_7 & & & \cdots \\ 0 & 0 & 0 & 0 & 0 & \pm Y & 0 & N_8 & & \\ 0 & +X & 0 & 0 & 0 & 0 & -X & 0 & N_9 & 0 \\ 0 & +X & 0 & 0 & 0 & 0 & 0 & -X & 0 & N_{10} \end{bmatrix}$$

In A_{DDM}, each I_{ji} element in the same column with node N_i means that the *ith* node connects to the *jth* node in that direction, thus its disassembly path is blocked in that direction in the present stage. Each I_{ij} element in the same row with node N_i means that the *ith* node is connected to the *jth* node from that direction, and its disassembly path is blocked in the opposite direction. For example, node 3 connecting node 4 in $\pm X,-Y$ directions, and being connected by node 1 from $+X,\pm Y$ directions, by node 2 from $-X,\pm Y$ directions. Therefore, in current disassembly stage node 3's disassembly paths are blocked in $\pm X,-Y$; -($+X,\pm Y$)=$-X,\pm Y$; -($-X,\pm Y$)=$+X,\pm Y$ directions correspondingly. Scanning all the nodes in matrix A_{DDM}, we can get the disassembly paths for each node in step 1. In this step only nodes 5, 6, 7, and 8 have non-*NULL* disassembly path result and thus can be removed from the assembly. By removing node N_i from the assembly, all the I_{ij} entries in the same column and row of A_{DDM} matrix are also cleared, releasing the disassembly paths to other nodes they were once blocked. Rescanning the existing nodes in the matrix, we can remove some of other components.

Repeat the process until all the nodes are removed, and the disassembly sequence is finally obtained. For the example coupling assembly:

$$\text{Step}\quad\begin{array}{r} 1: \\ 2: \\ 3: \\ 4: \end{array}\begin{bmatrix} NULL & NULL & NULL & NULL & -X & -X & +X & +X & NULL & NULL \\ -X & NULL & NULL & NULL & \backslash & \backslash & \backslash & \backslash & +X & +X \\ \backslash & +X & NULL & NULL & \backslash & \backslash & \backslash & \backslash & \backslash & \backslash \\ \backslash & \backslash & +Y & -Y & \backslash & \backslash & \backslash & \backslash & \backslash & \backslash \end{bmatrix}$$

Therefore the disassembly sequence is:

$$\{(N_5, N_6, N_7, N_8) \mapsto (N_1, N_9, N_{10}) \mapsto (N_2) \mapsto (N_3, N_4)\}$$

Note that the nodes in steps 1, 2 and 4 can be removed in a parallel mood respectively. During disassembly the exact sequence of parts to be removed may be different. After some nodes in step i are removed, the modes in step j ($j \geq i+1$) may be removable before all the ones in step i are removed, thus leading to different actual disassemble paths or even levels. If no node in step i is removed, then no nodes in step j ($j \geq i+1$) can be removed. To simplify the analysis, we assume that every node in each step should be removed completely before the nodes of the succeeding step can be removed.

In this example individual parts have been chosen as nodes for analysis, and the steps in the sequence have been determined as discussed before. In more complicated products with many clumps, to achieve different retirement goal, the decision of the 1st level nodes of clumps and further levels of nodes may vary, and thus bring different disassembly terminal nodes. The disassembly level of sequences may be different for various retirement purposes.

The complete disassembly sequence diagram can now be drawn out in Fig 5.7 for the assembly in Fig 5.6. Such a diagram is termed as reverse fishbone diagram [Lee and Ishii, 1996]

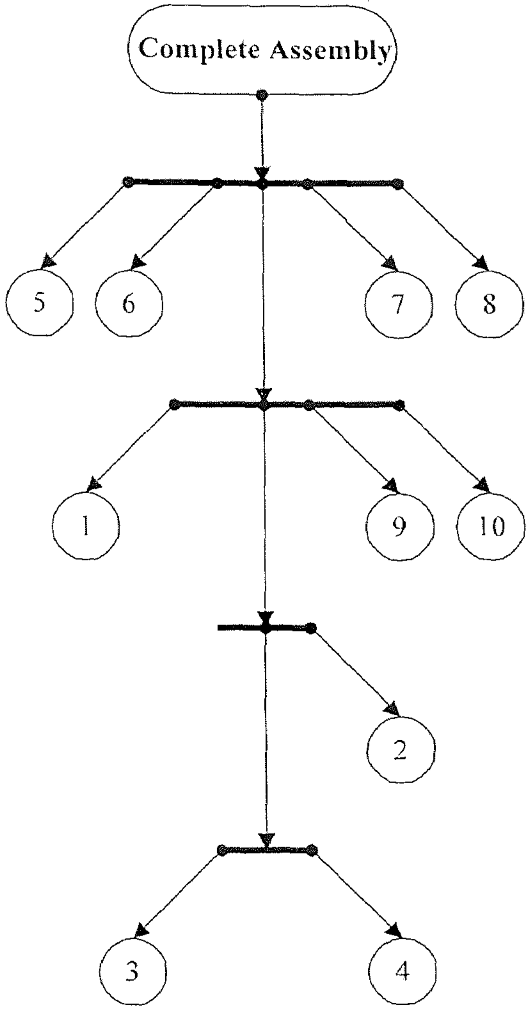


Fig 5.7 Complete Reverse Fishbone Disassembly Diagram of Assembly in Fig 5.6

CHAPTER 6

DESIGN FOR RETIRMENT OPTIMIZATION

In this chapter, we analyze the three elements important in the retirement optimization of a product: disassemblability and disassembly cost, the design of clumps and its effect on retirement optimization, the selection of parts concerning the life cycle environmental costs. All of these elements bring costs to the environment and affect a retirement plan in the environmental aspect. Because of the close relationships among them, designers must give a specified product a balance weighting of these engineering concerns to achieve the desired optimized result. This chapter gives a relative rating method for the Design-for-Retirement aspect.

6.1 Disassembly Rating Index

Continuing from the disassembly sequence optimization of the previous chapter, we can give the rating index of a disassembly. We will consider the rating in disassembly cost aspect with the general rules of making minimum disassembly cost, and unbrokenly taking out valuable components. The major disassembly concerns of clumps or component are:

- Accessibility, the disassembly level of a clump or component;
- Number of connection points to other clump or components on each mounting surface;

- Methods of connection, which decide the costs of disassembly of each connection point. We can define the major connection methods with their disassembly cost levels in an increasing order of cost as follows:
    - Type 1: Inserted, clipped, no treatment needed, cost level: 1
    - Type 2: Screwed, fasteners used, treatment needed, cost level: 2
    - Type 3: Welded or glued, special treatment needed, cost level: 3
    - Type 4: Permanent connection, e.g. being riveted, is broken during disassembly, cost level: 4
- Some directions are not available for clumps/components to be disassembled because of the clamping of heavy components.

Once the major points needing attention have been decided, we can proceed to the following disassembly and cost calculation procedure:

1. Decide the clumps formation of the product;
2. Mark the components or clumps which must be recycled or need special care due to their recycle value or damage effect to the environment;
3. Build the 1st level Node Information Matrix (NIM) with clumps as nodes;
4. Build the Disassembly Direction Matrix (DDM) for 1st level NIM, with consideration of the forbidden direction due to product clamping, and generate the disassembly sequence, mark each node with its corresponding disassembly sequence. This will be useful when the cost of must-be-taken components or clumps is calculated;

5. Repeat the process for clumps need to take apart until the disassembly intention has been achieved or disassembly optimization limits have been reached;

6. Find out the connection points on each mounting surface and build the

   Mounting Points Matrix (MPM): $A_{MPM} = \begin{bmatrix} N_1 & 0 & \dots & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ P_{i1} & \dots & N_i & \dots & \dots \\ \dots & \dots & \dots & \dots & 0 \\ P_{n1} & \dots & P_{ni} & \dots & P_n \end{bmatrix}$

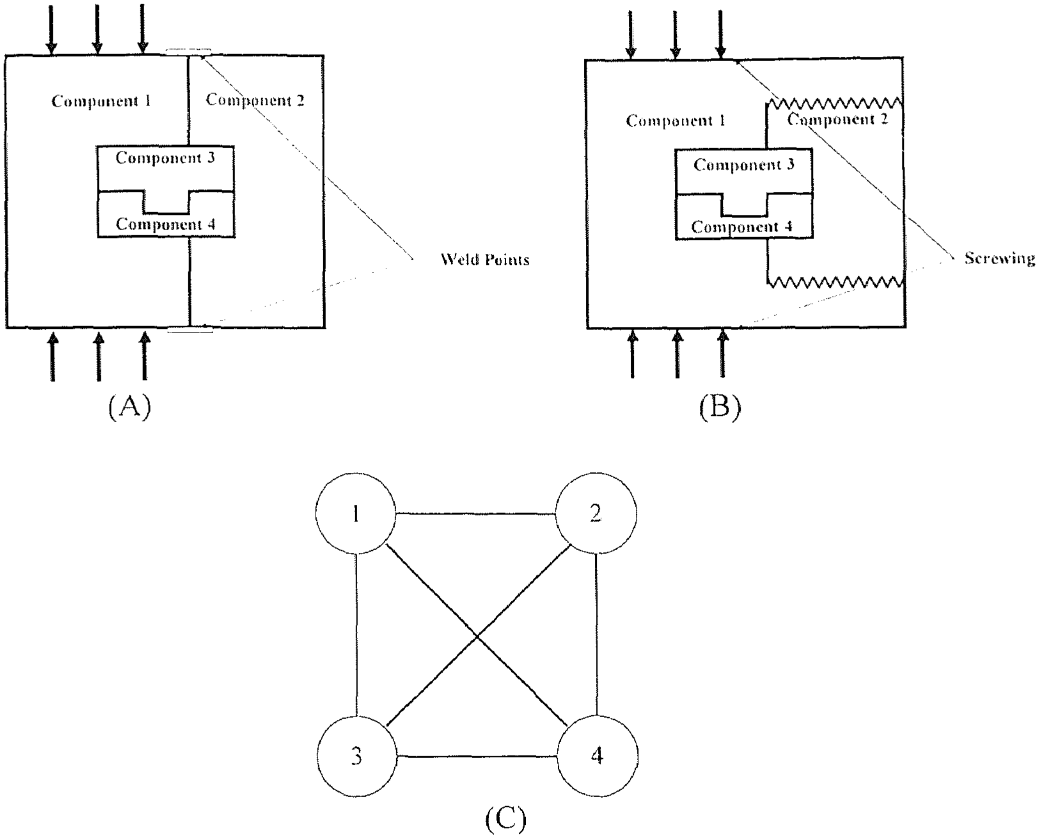
   Where N_i is the information data structure of the *ith* node, and

   P_{ij} is the data structure holding the information on mounting points between nodes *I* and *j*, e.g., the number of mounting points (sliding connections or other connections with no fasteners used counts as one point), mounting methods of points, mounting and dismounting directions, and dismounting cost;

7. After the MPM is built, calculate the disassembly costs. Following the already built disassembly sequence, take off the first clump/component and calculate its disassembly cost regarding to the number and connection methods of mounting points to other clumps/components, and add the result to its node information data structure N_i. If it has more than one Type 1 connection to other clumps/components, count them as one;

8. Repeat the process for each node until all the nodes have been taken off, add all the disassembly costs in the N_i data structure and then we can calculate out the overall disassembly cost.

To make our points more clear, we finish this section with an example that compares two assemblies as shown in Fig 6.1. The assembly in Fig 6.1(A) is similar to a test assembly in [Srinivasan et al., 1997].



(A)

(B)

(C)

Figure 6.1 Two Assemblies Example (A) (B), and their Connectivity Diagram (C)

In Assembly A of Fig 6.1, parts 1 and 2 are welded together and hold parts 3 and 4 in place. Parts 3 and 4 hold to each other with a convex of part 3. In Assembly B, parts 1 and 2 are screwed together instead, giving the same outside shape and volume. For the convince of disassembly, part 1 which is the heaviest is clamped. Assume that the disassembly costs are 1 to 4 for connection type 1 to type 4. Then we can build the Mounting Points Matrices M(A) and M(B) of the two assemblies as follows:

$$M(A)=\begin{bmatrix} N_1 & 0 & 0 & 0 \\ [2,6] & N_2 & 0 & 0 \\ [1,1] & [1,1] & N_3 & 0 \\ [1,1] & [1,1] & [1,1] & N_4 \end{bmatrix} \text{ and } M(B)=\begin{bmatrix} N_1 & 0 & 0 & 0 \\ [1,2] & N_2 & 0 & 0 \\ [1,1] & [1,1] & N_3 & 0 \\ [1,1] & [1,1] & [1,1] & N_4 \end{bmatrix}$$

Assembly A Assembly B

Where in entry [P_1, P_2], P_1 represents the number of connection points to the other component specified in the matrix, and P_2 represents the total disassembly cost to take apart these two components. We assume that every connection point using the same method has the same cost. From the discussion of Chapter 5, the disassembly sequences of these two assemblies are the same: $\{(N_2) \mapsto (N_3, N_4) \mapsto (N_1)$. At the end of the sequence we can obtain all the disassembly costs for Fig 6.1 in Table 6.1 in next page:

Table 6.1 Disassembly Costs of Two Assemblies in Fig 6.1

Assembly A		Assembly B	
Remove N_2 from connection to N_1 and N_3, N_4 subassembly:	6+1=7	Remove N_2 from connection to N_1 and N_3, N_4 subassembly:	1*2+1=4
Remove N_3 and N_4 :	1	Remove N_3 and N_4:	1
Take N_3 and N_4 apart:	1	Take N_3 and N_4 apart :	1
Overall disassembly cost: 9		Overall disassembly cost: 6	

There is a trick when removing other clumps/components off and leaving only one clump /component in the assembly, we can view this as taking the last clump/component from the assembly. In step 2 we remove clumps $(N_3\ N_4)$, as equivalently, we can view this as taking N_1 from the assembly. We can find that the disassembly cost of assembly B is lower than that of Assembly A. We conclude that design B is better for disassembly than design A. Because that the connection between components 1 and 2 in assembly B is easier for disassembly than used in Assembly A.

6.2 Clump Choice Optimization

Clump is the base of our analysis of Design-for-Retirement. In most cases of post life recycle, clump is a major functional portion of a product, which is a collection of components and subassemblies forming a certain function and share the same post life treatment based upon the design intent. In our concern of environmental impact, a clump falls into three major categories regarding their design intent for post life recycle:

- For re-use, which requires minimum disassembly cost. This category's clump should have high recycle value to balance the reprocessing cost;
- For re-cycle, this requires material value and the fastening method be compatible with recycle technology used in it, which means the balance of recycle cost and recycle value-gain;
- For disposal. In this case, the only concerns are to make minimum its disassembly cost and environmental impact.

Products also vary in their formation of clump size and complexity. Large and complex clumps like transmission and engine in an automobile power train (which actually are subassemblies) are easy to be disassembled but will require more cost when reprocessing them for reuse. Small but complex clumps like the electrical components in a cellular phone set may demand high cost to be disassembled intact and even more cost to recondition for reuse. With a high out-of-date rate, disposal may be the most economical choice for these kinds of products.

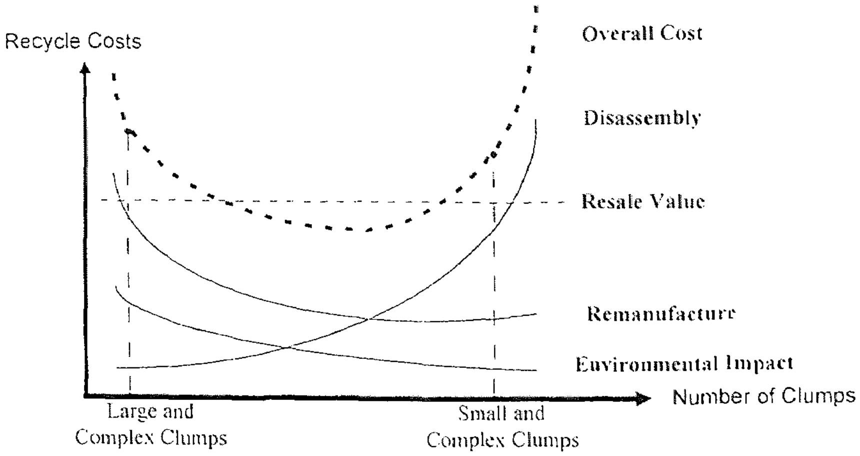


Fig 6.2 Recycling Costs Model

Following the Simplified Recycling Model [Ishii et al., 1994], as shown in Fig 6.3, neither Large-and-Complex nor Small-and-Complex clump choices are economically profitable given the market resale value and environmental cost. Clumps should be designed to make their overall recycle costs below the resale value.

6.3 Retirement Optimization

The optimized retirement plan of clumps with specified design intention for post life recycle can also be treated within three major categories: to be reused, to be recycled as material, and to be disposed as waste. In each category recycling planers deal with the relationships of clump/component reference values with various considerations. The values include:

$V_{\text{new part}}$, V_{resale}, V_{material} ,

C_{disposal}, $C_{\text{material process}}$, $C_{\text{disassembly}}$,

$C_{\text{out-of-date lose}} = V_{orginal} * \left(1 - e^{-\alpha t}\right)$, where α is the out-of-date rate of clump/part

$C_{\text{remanufacture}} = V_{orginal} * e^{-\lambda t}$, where λ is the degradation rate of clump/part

Using these values, we can decide which treatment should be used on a retired clump/component by calculating the Gain of each treatment and choose the one with maximum Gain, which is *Gain = Benefit - Cost.*

For clump/component to be reused:

$$Cost = C_{\text{disassembly}} + C_{\text{remanufacture}} + C_{\text{out-of-date lose}}$$

$$Benefit = V_{\text{resale}}$$

$$Gain = Benefit - Cost$$

$$= V_{\text{resale}} - C_{\text{disassembly}} - C_{\text{remanufacture}} - C_{\text{out-of-date lose}}$$

For clump/component to be recycled as material:

$$Cost = C_{\text{disassembly}} + C_{\text{material process}}$$

$$Benefit = V_{\text{material}}$$

$$Gain = V_{\text{material}} - C_{\text{disassembly}} - C_{\text{material process}}$$

For clump/component to be disposed:

$$Cost = C_{\text{disassembly}} + C_{\text{disposal}}$$

$$Gain = -Cost = - C_{\text{disassembly}} - C_{\text{disposal}}$$

Once the functions have been defined, we can calculate and compare all the Gain values to make decision of which treatment to use on the clump/component under consideration. If Gain values from Reuse and Material Recycle give lower values than the values from Disposal, it means the total cost of reprocessing and disassembly have not only overrun the benefit and also exceed the disposal cost, in such case, disposal will be the best retirement plan.

6.4 Examples

In this section two designs of a Personal Computer (PC) will be discussed. We choose PC as an example because PC products are highly modularized, have a rapid lifecycle, and bring great recycling needs of PC components. Most PC products are outdated for retirement rather than worn out for retirement.

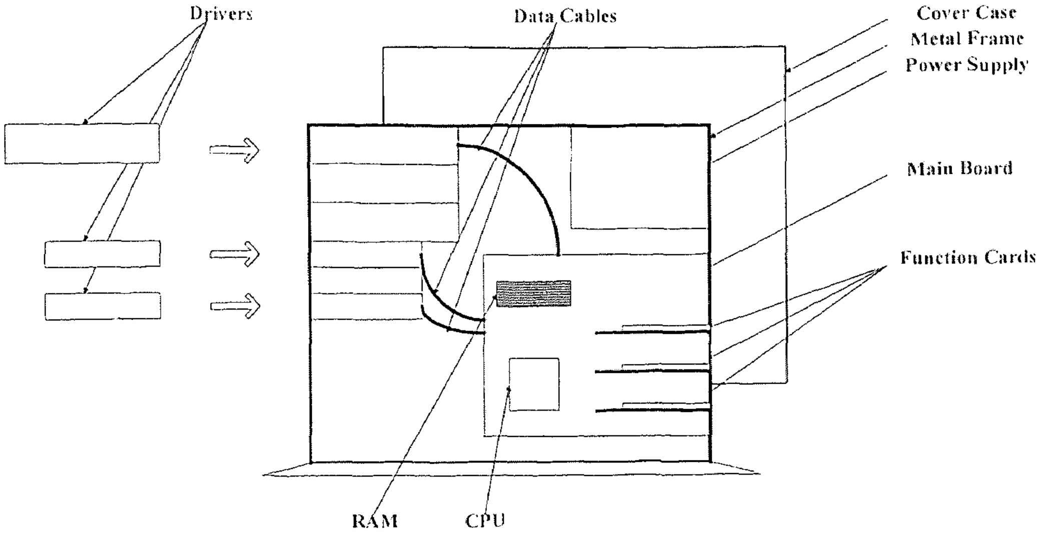


Fig 6.3(A) Conventional Low Cost PC Mini-Tower (Design 1)

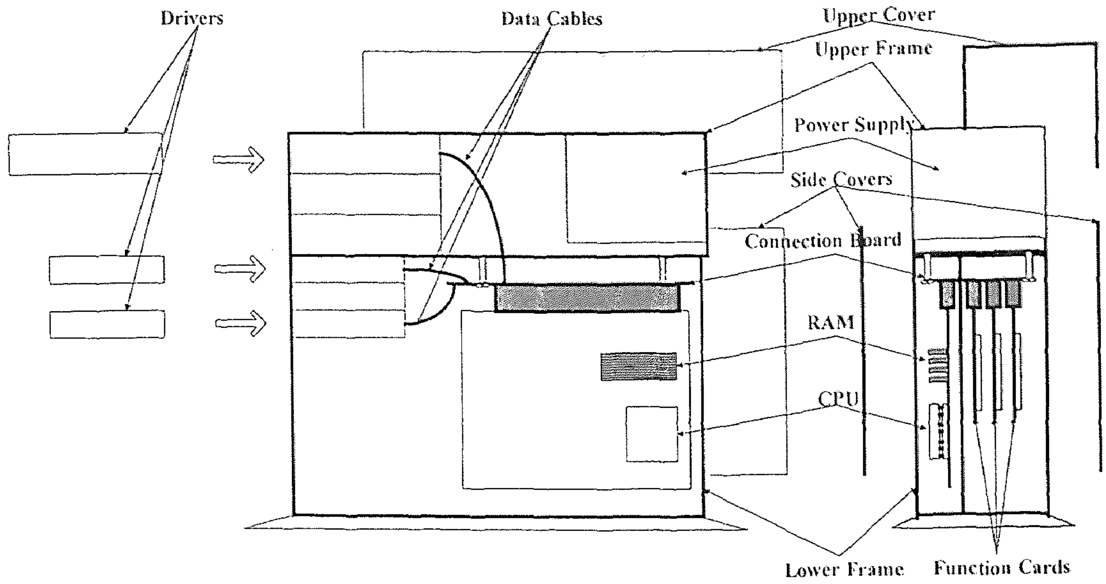


Fig 6.3 (B) Improved Mini-Tower Design by Compaq Computer (Design 2)

Fig 6.4 shows the examples of two different PC architectures, where (A) represents some kind of conventional low cost designs, and (B) is an architecture used by Compaq mini-tower computers.

The detailed disassembly costs for the two designs are assumed as follows in Table 6.5 in the next page (here, "PC Cards" represents "Function Cards"). To compare the two designs in disassemblability aspect, we follow these steps:

- Build the Disassembly Direction Matrix (DDM) of these two assemblies.
- Derive the disassembly sequence of these two assemblies from the DDMs.
- Build the Mounting Point Matrix (MPM) of them and calculated the detailed disassembly costs.

Table 6.2 Detailed Disassembly Costs of PC Design 1 and 2

ID	Component Name	Connection Method	Cost per operation	Subtotal
C_1	Cover Case (design 1)	6 screws	0.5	3
C_2	Upper Cover (design 2)	2 screws	0.5	1
C_3	Side Covers (design 2)	2 screws	0.5	1
C_4	Data cables (design 1 and 2)	2 plugs	0.5	1
C_5	Drivers (design 1 and 2)	4 screws	0.5	2
C_6	PC Cards (design 1 and 2)	1 screw, 1 plug	0.5	1
C_7	Main Board (design 1)	4 screws	0.5	2
C_8	CPU board (design 2)	1 screw, 1 plug	0.5	1
C_9	Connection Board (design 2)	4 screws	0.5	2
C_{10}	CPU (design 1 and 2)	1 special plug	2	2
C_{11}	SIMM RAM (design 1 and 2)	4 Special plugs	1	4
C_{12}	Power Supply (design 1 and 2)	4 screws	0.5	2
C_{13}	Metal case frame (design 1)	\	\	\
C_{14}	Upper case frame (design 2)	\	\	\
C_{15}	Lower case frame (design 2)	\	\	\
C_{16}	Upper/Lower Case Connection (design 2)	4 screws	0.5	2

First we build the DDM of design 1 and design 2 from Fig 6.4:

The DDM of Design 1 is:

$$\begin{bmatrix}
C_1 & 0 & \cdots & & \cdots & & \cdots & & 0 \\
[\pm X,-Y] & C_5 & 0 & \cdots & & \cdots & & \cdots & \\
[\pm X,-Y] & [+X] & C_4 & 0 & \cdots & & \cdots & & \cdots \\
[\pm X,-Y] & 0 & [-Y] & C_7 & 0 & \cdots & & \cdots & \\
[\pm X,-Y] & 0 & 0 & [\pm Y] & C_6 & 0 & \cdots & & \cdots \\
[\pm X,-Y] & 0 & 0 & [\pm Y] & 0 & C_{10} & 0 & \cdots & \\
[\pm X,-Y] & 0 & 0 & [\pm Y] & 0 & 0 & C_{11} & 0 & \cdots \\
[-X,-Y] & [+X,\pm Y] & 0 & [+X,\pm Y] & [\pm Y] & 0 & 0 & C_{13} & 0 \\
[\pm X,-Y] & 0 & 0 & 0 & 0 & 0 & 0 & [-X,\pm Y] & C_{12}
\end{bmatrix}$$

The disassembly steps of Design 1 are:

$$\begin{bmatrix}
[+Y] & NULL & NULL & NULL & NULL & NULL & NULL & NULL & NULL \\
\backslash & [-X] & [+X,+Y] & NULL & NULL & NULL & NULL & NULL & NULL \\
\backslash & \backslash & \backslash & [-X] & [\pm X] & NULL & NULL & NULL & NULL \\
\backslash & \backslash & \backslash & \backslash & \backslash & [\pm X] & [\pm X] & [+X] & [-X]
\end{bmatrix}$$

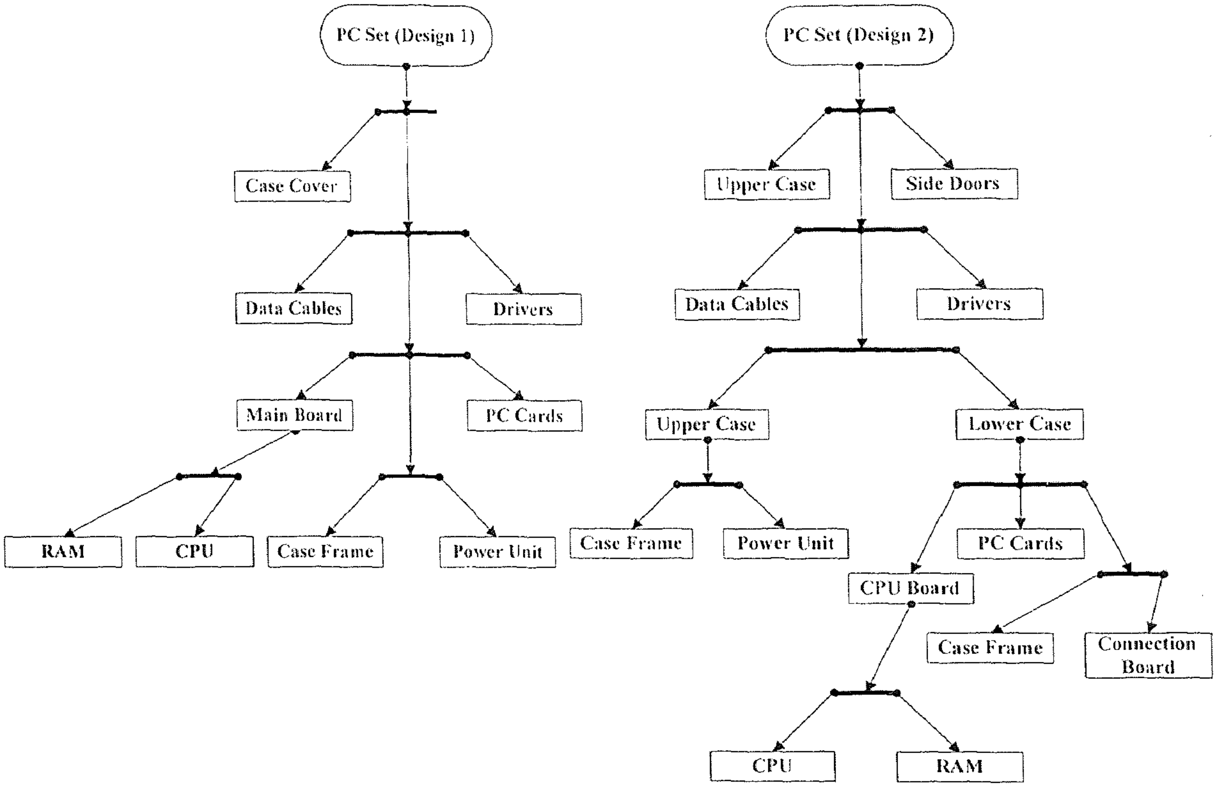
The DDM of Design 2 is:

$$\begin{bmatrix}
C_2 & 0 & & \cdots & & \cdots & & \cdots & & \cdots & & 0 \\
0 & C_3 & 0 & & \cdots & & \cdots & & \cdots & & \cdots & \\
0 & [-X,\pm Y] & C_4 & 0 & & \cdots & & \cdots & & \cdots & & \cdots \\
0 & [-X,\pm Y] & [-X] & C_5 & 0 & & \cdots & & \cdots & & \cdots & \\
[-X,\pm Y] & 0 & 0 & [+X,\pm Y] & C_{14} & 0 & & \cdots & & \cdots & & \cdots \\
0 & [-X,\pm Y] & 0 & [+X,\pm Y] & [-Y] & C_{15} & 0 & & \cdots & & \cdots & \\
0 & [-X,\pm Y] & 0 & 0 & 0 & [-X] & C_8 & 0 & & \cdots & & \cdots \\
0 & [-X,\pm Y] & 0 & 0 & 0 & [-X] & 0 & C_6 & 0 & & \cdots & \\
0 & [-X,\pm Y] & [-Y] & 0 & 0 & [\pm X,-Y] & [+Y] & [+Y] & C_9 & 0 & & \cdots \\
0 & [-X,\pm Y] & 0 & 0 & 0 & 0 & [\pm Y] & 0 & 0 & C_{10} & 0 & \\
0 & [-X,\pm Y] & 0 & 0 & 0 & 0 & [\pm Y] & 0 & 0 & 0 & C_{11} & 0 \\
[-X,\pm Y] & 0 & 0 & 0 & [-X,\pm Y] & 0 & 0 & 0 & 0 & 0 & 0 & C_{12}
\end{bmatrix}$$

The disassembly steps of Design 2 are:

$$\begin{bmatrix} [+X] & [+X] & NULL & NULL & NULL & NULL & NULL & NULL & NULL & NULL & NULL & NULL \\ \backslash & \backslash & [+X,+Y] & [-X] & NULL & NULL & NULL & NULL & NULL & NULL & NULL & NULL \\ \backslash & \backslash & \backslash & \backslash & [+Y] & [-Y] & NULL & NULL & NULL & NULL & NULL & NULL \\ \backslash & \backslash & \backslash & \backslash & \backslash & \backslash & [-X] & [-X,-Y] & NULL & NULL & NULL & [-X] \\ \backslash & \backslash & \backslash & \backslash & \backslash & \backslash & \backslash & \backslash & [-Y] & [\pm X] & [\pm X] & \backslash \end{bmatrix}$$

From these results we can build the complete disassembly tree of these two designs. Fig 6.4 shows the complete disassembly tree structures of designs 1 and 2. Each PC is assumed to use three Drivers (HDD, FDD, and CD-ROM driver) and three Function Cards (PC cards).



(A) (B)

Fig 6.4 Disassembly Tree of PC (A) Design 1 and (B) Design 2

Following the procedure presented in Section 6.1, and walk through every step disassembly sequences, the complete disassembly costs of these two designs can be calculated by employing the MPM matrices as follows:

The MPM of Design 1 is:

$$\begin{bmatrix} N_1C_1 & & \cdots & & \cdots & & \cdots & & 0 \\ 0 & N_2C_5 & & \cdots & & \cdots & & \cdots & \\ 0 & [3,1.5] & N_3C_4 & & \cdots & & \cdots & & \cdots \\ 0 & 0 & [3,1.5] & N_4C_7 & & \cdots & & \cdots & \\ 0 & 0 & 0 & [3,1.5] & N_5C_6 & & \cdots & & \cdots \\ 0 & 0 & 0 & [1,2] & 0 & N_6C_{10} & & \cdots & \\ 0 & 0 & 0 & [4,4] & 0 & 0 & N_7C_{11} & & \cdots \\ [6,3] & [3,6] & 0 & [4,2] & [3,1.5] & 0 & 0 & N_8C_{13} & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & [4,2] & N_9C_{12} \end{bmatrix}$$

The complete disassembly cost can then be calculated by equation:

$Cost = \sum_{i=1}^{n} Cstepi$, where n represents number of steps and

$Cstepi = \sum_{j=1}^{m} Coperation$, where m represents number of operations in each step

Thus the disassembly cost of Design 1 is:

$$Cost = \underline{(3)}_{\text{step1}} + \underline{(3*1+3*2)}_{\text{step2}} + \underline{(3*1+2)}_{\text{step3}} + \underline{[(4+2)+(2)]}_{\text{step4}} = 25$$

The disassembly cost of Design 2 is:

$$Cost = \underline{(2*1+1)}_{\text{step1}} + \underline{(3*1+3*2)}_{\text{step2}} + \underline{(4*0.5)}_{\text{step3}} + \underline{(1+3*1+2)}_{\text{step4}} + \underline{(2+4+2)}_{\text{step5}} = 28$$

As shown above, to reach a complete disassembly, design 2 costs more to disassemble than design 1, as suggested by Design 2's more complex disassembly tree. But in most cases, a PC to be demanufactured does not need a complete disassembly. Usually only parts to be replaced are removed from the assembly. In other words, selective disassembly is a common situation in the PC demanufacturing. In the following, we compare several major activities in PC recycle and explore the retirement treatment benefits of design 2.

These activities include:

- Replacing the CPU and RAM chips;
- Replacing function cards like the video adapter card and modem card;
- PC update, which replaces CPU, RAM, function cards, and electrical board with newer ones. (Note that an electrical board carries the main data bus, BIOS, CPU and RAM slots).

Figures 6.5 through 6.7 show the tree structures of major selective disassemblies.

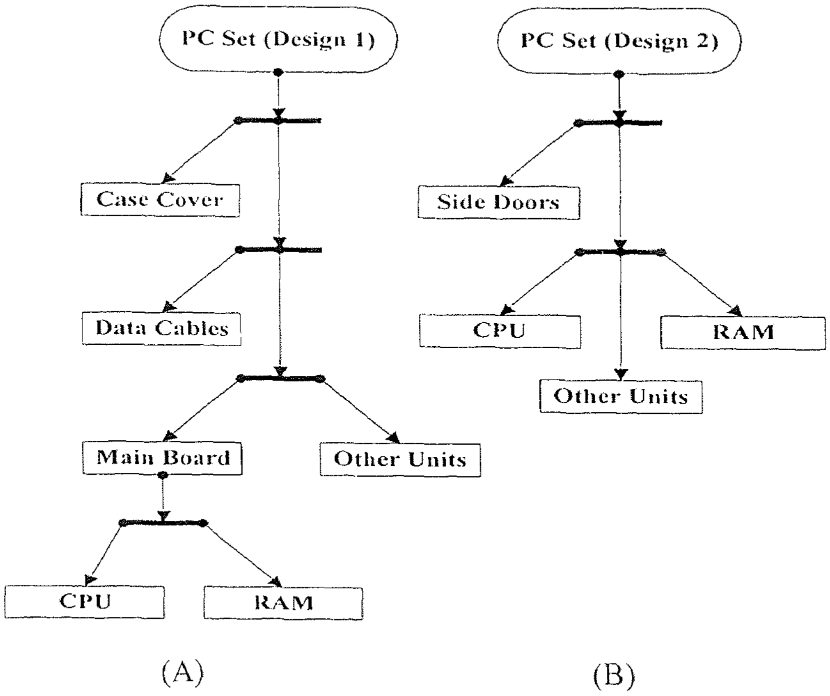


Fig 6.5 Replacement of CPU and RAM in (A) Design 1 and (B) Design 2

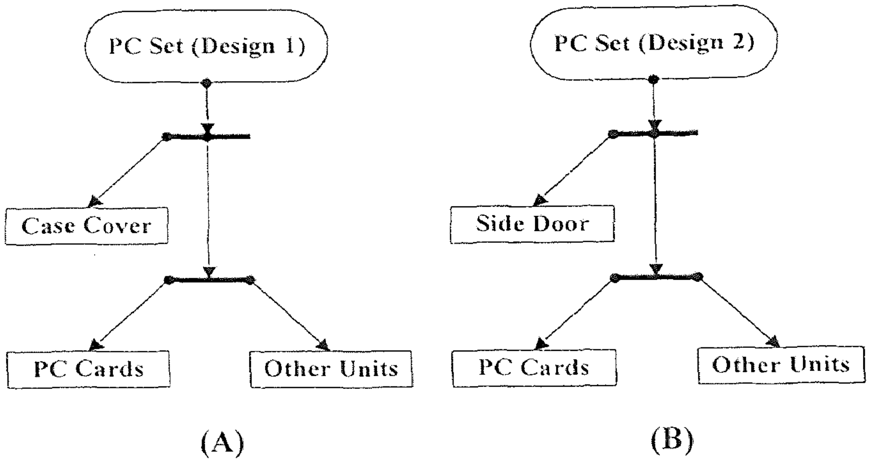


Fig 6.6 Replacement of PC Function Cards in (A) Design 1 and (B) Design 2

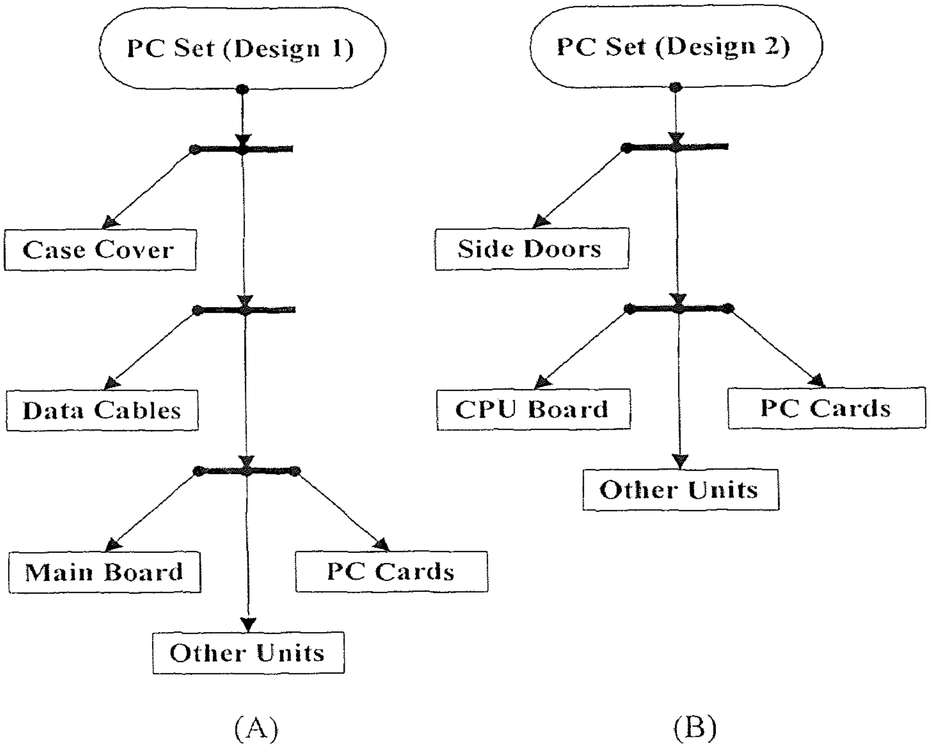


Fig 6.7 PC Update in (A) Design 1 and (B) Design 2

The disassembly costs for each of these selective disassembles can be calculated as shown in Table 6.3. We can see that Design 2 is more cost-effective over design 1 in these cases. In Table 6.10, the Costs are calculated with the equations in page 15.

Table 6.3 Disassembly Costs of Selective Disassemblies

CPU, RAM Replacement	$\text{Cost}_{\text{Design 1}}=3+1*3+2+(2+4)=14$	$\text{Cost}_{\text{Design 2}}=1*2+(2+4)=8$
PC Cards Replacement	$\text{Cost}_{\text{Design 1}}=3+1*3=6$	$\text{Cost}_{\text{Design 2}}=1+1*3=4$
PC Update	$\text{Cost}_{\text{Design 1}}=3+1*3+(2+1*3)=11$	$\text{Cost}_{\text{Design 2}}=1*2+(1+1*3)=6$

Next we explore retirement optimization and the corresponding overall costs of these two designs. We assume the reference values of the two designs as in Table 6.4 on next page. And the PCs are going to retire after two years of usage with one year as the standard calculation period.

Table 6.4 Detailed Reference Values of Components in Design 1 and 2

	CPU Chip	RAM Chips	Video Card	Modem Card	Main Board (design 1)	CPU Board (design 2)
$V_{\text{new part}}$	250	300	150	120	400	200
V_{material}	2	2	3	3	4	4
V_{resale}	125	250	100	75	150	150
$C_{\text{disassembly}}$ (design1/2)	14 / 8	14 / 8	6 / 4	6 / 4	11	6
λ (degradation rate)	0.0693	0.0693	0.139	0.139	0.0693	0.0693
$C_{\text{remanufacture}}$	32	39	36	29	51.2	25.6
α (out-of-date rate)	0.693	0.173	0.139	0.277	0.277	0.139
$C_{\text{out-of-date lose}}$	187.5	87.7	36	51	97.1	48.5
C_{disposal}	2	2	4	4	6	6

Using the components values in Table 6.4 and the functions in Section 6.3, we can obtain the retirement Gain values of these two designs as shown in Table 6.5:

Table 6.5 Retirement Gain of Designs 1 (D1) and 2 (D2)

Components	**Reuse Gain**		**Material Recycle Gain**		**Disposal Gain**	
	D1	**D2**	**D1**	**D2**	**D1**	**D2**
CPU Replacement	-108.5	-102.5	-44	-38	-16	-10
RAM Replacement	109.3	115.3	-51	-45	-16	-10
Video Card Replacement	22	24	-39	-37	-10	-8
Modem Card Replacement	-11	-9	-32	-30	-10	-8
CPU/Main Board	-9.3	69.9	-58.2	-27.6	-17	-12

From the calculated Gains shown in Table 6.5, we can make decisions of optimized retirement plans for each component after their two years of usage:

1. CPU chip should be disposed, with Gain –16 for design 1 and –10 for design 2;
2. RAM chips should be reused with Gain 109.3 for design 1 and 115.3 for design 2;
3. Video card should be remanufactured and reused with Gains 22 and 24 for design 1 and 2 respectively;
4. Modem card should be disposed, with Gain –10 and –8 for designs 1 and 2 respectively;

5. CPU or Main Board will be reused with Gain –9.3 for design 1 and 69.9 for design 2. Note that the better architecture of design 2 has made the reuse of CPU board economically beneficial after a life cycle of two years, while the reuse of Main Board in design 1 leads to the minimum cost.

From the above analysis, we can conclude that Design 2 gives higher Gains in each retirement choice we considered in Table 6.5. This is because of the consideration of post life retirement and the employment of modular components in the design.

CHAPTER 7

CONCLUSION

7.1 Contributions

This thesis deals with the disassembly sequence generation and cost analysis in the Design-For-Retirement engineering aspect, and develops a method to rate different designs by considering both cost and environmental impact.

The contributions of this thesis are summarized as follows:

1. Several basic concepts about the product environmental concerns are introduced: Design-For-Disassembly, Design-For-Environment, Design-For-Retirement, and Retirement Optimization. The whole process covering the material, manufacturing, customer usage, disassembling, and recycling stages of a product lifecycle is overviewed. It also analyzed the cost-environmental relationship between the material choice and engineering complexity issues.
2. The assembly and disassembly sequence planning analysis process is discussed. The major representational problems of a product assembly geometric structure, disassembly paths and retirement plans are indicated. This thesis also reviews the costs related to the choice of individual parts and previews work over a parts selection optimization algorithm.
3. The problems of disassembly cost optimization and product rating in the environmental aspect are discussed. A matrix based representation model of product disassembly information (Node Information Matrix) is proposed and a method is developed to generate disassembly sequence of a product represented by such a matrix.

4. It develops a set of equations describing the relationships among various costs of a product recycle process. These equations work with the product information representation model to rate a product design in the environmental aspect.
5. The proposed concepts and methods are demonstrated by rating two different PC designs. One is a conventional PC design and the other is a retirement-optimized design by Compaq Computer. The comparison of retirement costs of these two designs answers why the Compaq design is better from the environmental impact/cost view point.

7.2 Future Work

The discussion of the Design-For-Retirement aspect could expand to a vast range from product market value variation to material and parts manufacturing technologies used. Due to the limited time, this thesis is confined to the disassembly sequence generation and disassembly plan optimization with respect to its benefit gain and penalty. The Node Information Matrix proposed in this thesis has a data structure N_i that can hold various information of product components. Further development could utilize these data structures to integrate parts lifecycle cost analysis with the disassembly planning in a computer algorithm form, and build a computerized representation of the models developed in this thesis.

In this thesis, disassemble directions considered are only $\pm X$, $\pm Y$, and $\pm Z$ directions. In most cases of consumer electronics which is the main analysis target of this thesis, parts disassemble directions are either along $\pm X$, $\pm Y$, $\pm Z$ or not of vital importance to disassembly analysis in such examples as cable connections. But in some complicated products such as automobile engine, parts disassemble directions are of vital importance and many not be simplified as the $\pm X$, $\pm Y$, $\pm Z$ directions only. Further analysis method should be developed to take these kind of cases into consideration when needed.

Another interesting area that needs further discussion is the clump design and its effect on the product retirement planning. As discussed in this thesis, clumps are considered as the basic recycling units that are recycled as used functional parts. The number of clumps, clump assembly complexity, material/technology used in clumps and the designed recycle intention of clumps all make different retirement plans. Clumps can also be treated as a tree structure, and can contain substructures consisting of parts as nodes.

Another

The final goal of the Design-For-Retirement analysis is to give a designer a complete computer aided tools set to estimate the retirement timing and cost of their designs. These tools should be built on the PC or other operating platforms. The input methods can adopt the methods of an input-form, spreadsheet-based inputs, and/or visually graphic inputs. The output should contain the suggested retirement time, retirement plan of clumps/parts, and overall gain or rating of the designs under investigation.

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