# Design of disassembly systems : a systematic approach



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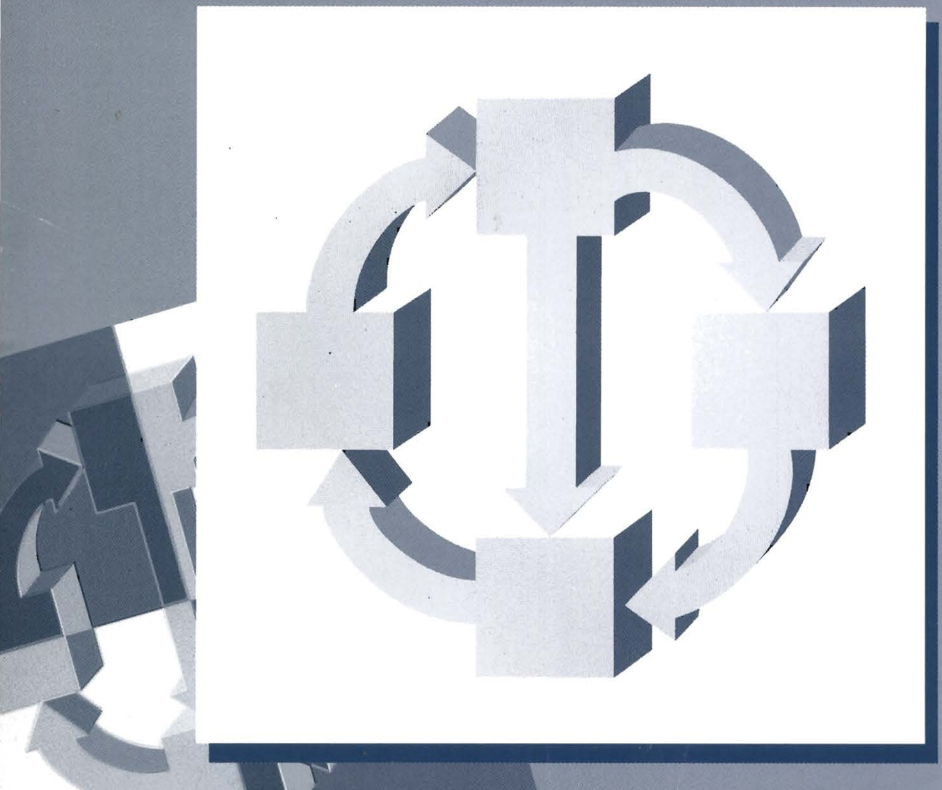

**Kiril Penev**

# Design of Disassembly Systems:

## a systematic approach

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**PROEFSCHRIFT**

ter verkrijging van de graad van doctor aan de
Technische Universiteit Eindhoven
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voor een commisie aangewezen door het College van
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door

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geboren te Sofia

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# Preface

The research presented in this dissertation concerns the systematic design of disassembly systems. Such systems are required for the recovery of the increasing flow of discarded goods. The aim is to generate a certain profit from recovery, while fulfilling legislation and environmental requirements.

The practical relevance of this research can be realized by the increasing need to recover discarded goods, because they have an undesirable environmental impact. Moreover, this issue can be regarded as a business opportunity that can be used by companies to generate profit. The scientific value may be demonstrated by the increasing number of scientific papers that have been published in the last few years.

Parts of this research were presented, among other things, during various international conferences, such as "Lean/Agile Manufacturing in the Automotive Industries" (Aachen, Germany), "Environmentally Conscious Design and Manufacturing" (Las Cruces, USA) and "Engineering Design" (Prague, Czech Republic), and were published in well-known journals, such as the "Journal of Industrial Engineering", "Technovation" and "International Journal of Production Research".

However, this dissertation could not have been completed without the support of many people. Therefore, I wish to thank a number of people who contributed the most to this research, realizing that the list will be incomplete.

First of all, I would very much like to thank Prof. Piet Sanders for the opportunity he gave me to begin my real working career in the Netherlands. Without getting this opportunity I would not have been able to accomplish this dissertation. For me it was not only a pleasure to discuss technical issues related to this research with him, but also general aspects of life. In brief, his integral support during those years was indispensable for my final achievements.

Similarly, I am very grateful to my co-promotor Ad de Ron. We started working together at the beginning of this research and we went through all phases until it was completed. His permanent support and on-line discussions were one of the key factors for the obtained results. Also I thank him for his pleasant company during our business trips to Eastern Europe.

I thank Prof. Jan van Bragt for everything I learned from him during the design course and for the valuable comments and recommendations for the completion of this dissertation. The other committee members Prof. Han Brezet and Prof. Egbert-Jan Sol helped me to involve important aspects in this research and to complete the final version, for which I am very grateful.

I am particularly grateful to our industrial partners, among others, Jan Visser who gave us the opportunity to apply all developed ideas in practice, which was important in obtaining the practical results presented in this dissertation.

Several Master and post-graduate students participated in the case studies described in Chapter 6 and during the final completion of the dissertation's lay-out. Therefore, many thanks to Ruud Reynders, Paul in 't Zandt, Frank Kerssen, Ingrid de Pauw and Rob Schepens.

I would like to thank to all my colleagues of the Manufacturing Technology Group for their support and attention during all those years. The pleasant atmosphere that they created helped me a lot.

The members of the Department of the Automation of Discrete Production at the T.U. Sofia, especially Ilia Boyadjiev and Antony Ikonopisov, are gratefully acknowledged for providing the basic knowledge necessary to attempt and accomplish this dissertation successfully.

Last but not least I want to thank my parents, girl-friend and friends who supported me in whatever way they could during my stay in the Netherlands.

Kiril Penev
Eindhoven, 1996

# Summary

This dissertation concerns one of the subjects that will help establish sustainable production. It means that products are designed, produced, distributed, used, disassembled and recovered, and disposed of with minimal damage to the environment and minimal use of raw materials, energy and other resources. The aim is to save the globe for future generations. However, before new sustainable products can be designed and produced, the huge flow of discarded goods should be processed in an economic way, while including environmental aspects. With the accomplishment of this goal, the production chain can be closed and the basis for sustainable production can be established. For this purpose flexible disassembly systems should be designed and implemented, which are able to process the increasing amount of discarded goods now and in the future.

Chapter 1 describes the developments towards the establishment of a sustainable production. It clarifies the significance of disassembly as a weapon to solve the problems associated with the recovery of discarded goods. In addition, it provides the industrial engineering aspects that should be considered when approaching the design of disassembly systems. In this context, new terms and concepts are used to create a new terminology that is used for the purpose of this investigation. Finally, the aim of the dissertation is established, which is: *"to develop a comprehensive and systematic procedure to design and implement disassembly systems for the reuse of discarded goods".*

In Chapter 2 the most important developments in the field of recovery of discarded goods are presented. While all important aspects are regarded, particular attention is given to the developments concerning the design of disassembly systems. The aim of this literature review is to clarify what has been achieved in this area and what more should be done. It was found that the literature does not include a systematic approach for the design of disassembly systems, which justifies the objective of this dissertation.

Chapter 3 describes the basis for the development of a systematic approach. For this purpose the most important segments of engineering design are introduced: 1) a theory of technical systems, 2) design theory, 3) design methodology and 4) a theory of special processes and equipment. The emphasis lies on the assembly issues that can be used for disassembly purposes. In this context, an extensive analysis of the product design and assembly process was carried out and their link to disassembly is explained. The conclusion is that assembly has a big influence on disassembly and the level of mechanization and automation on the corresponding assembly and disassembly system. A practical case shows how design for easy assembly makes the introduction of a high automated assembly system possible.

Chapter 4 suggests a method for the determination of the disassembly strategy. It consists of three main issues: 1) generation of the number of feasible disassembly plans, 2) determination of the profits of every disassembly step and 3) determination and application of the optimal disassembly process. The aim of this method is to establish the most feasible process to recover the discarded goods. In this context, the determination of the disassembly strategy is considered to be the core of the entire development process. The suggested method is clarified with a practical example.

The complete systematic approach for the design of disassembly systems is described in Chapter 5. It consists of five main phases which are divided into a number of steps. They are described in detail and their importance concerning the recovery of discarded goods is clarified. In addition, the place of disassembly systems is given in a complete product life cycle model. There the relationships with the other segments and their role within a sustainable production chain can clearly be seen.

The application of the systematic approach is presented in Chapter 6. It concerns the disassembly and recovery of household appliances and consumer electronics goods. These cases show the universal applicability of the suggested systematic approach for the determination of the disassembly strategy and the design of disassembly systems. The satisfactory results obtained in practice prove the benefit from the introduction of disassembly systems. In addition, some design guidelines for the development of disassembly and recovery friendly products were developed on the basis of practical experience.

Finally, in Chapter 7, the conclusions and recommendations for further research can be found.

# Samenvatting (Summary in Dutch)


Om tot een duurzame ontwikkeling te komen is het noodzakelijk dat produktketens gesloten worden, dat het energiegebruik wordt verminderd en dat de produktkwaliteit wordt verbeterd. Dit betekent onder meer dat produkten zo ontworpen, geproduceerd, gedistribueerd, gebruikt en teruggewonnen dienen te worden, dat zo min mogelijk milieuschade ontstaat en natuurlijke bronnen zo min mogelijk worden gebruikt. Het sluiten van produktketens betekent dat afgedankte goederen of componenten of materialen dienen te worden teruggewonnen. Daartoe kunnen in de toekomst produkten zo ontworpen worden dat dit op een eenvoudige goedkope manier kan plaatsvinden. Echter, de enorme hoeveelheid goederen die nu afgedankt worden, zijn niet ontworpen om teruggewonnen te worden. Dit betekent dat een economisch verantwoorde bedrijfsvoering ten aanzien van het terugwinnen moeilijk is. In dit proefschrift wordt een systematische methodologie ontwikkeld, waarmee demontagesystemen voor het terugwinnen van afgedankte goederen kunnen worden ontworpen. Hiermee wordt een bijdrage geleverd aan de verbetering van een economisch verantwoorde bedrijfsvoering en worden onzekerheden hierin verkleind, terwijl tevens een bijdrage wordt geleverd aan de bewerking van de als maar toenemende hoeveelheid afgedankte goederen.

In Hoofdstuk 1 worden ontwikkelingen beschreven die nodig zijn om tot een duurzame produktie te kunnen komen. Hieruit blijkt de belangrijke rol die demontage-activiteiten in verband met de terugwinning van afgedankte goederen kunnen spelen. Verder worden bedrijfskundige aspecten aangegeven die voor het ontwerpen van demontagesystemen van belang zijn. Hierbij worden nieuwe termen en concepten geïntroduceerd teneinde een eenduidige en goed gefundeerde terminologie te verkrijgen. Tenslotte wordt het doel van het onderzoek beschreven, te weten: *"het ontwikkeling van een samenhangende en systematische ontwerpmethodologie voor demontagesystemen voor de terugwinning van afgedankte goederen".*

In Hoofdstuk 2 worden de belangrijkste ontwikkelingen beschreven die zich de afgelopen jaren op het gebied van de terugwinning van afgedankte goederen hebben voorgedaan. Het doel van deze literatuurstudie is om duidelijkheid te verkrijgen over hetgeen op dit gebied bereikt is, en hetgeen nog verder onderzocht moet worden. Op grond van deze literatuurstudie is geconcludeerd dat onderzoek nodig is betreffende een systematische methodologie voor het ontwerpen van demontagesystemen; dit onderzoek wordt in deze dissertatie beschreven.

De basis voor de ontwikkeling van een systematische ontwerpmethodologie wordt in Hoofdstuk 3 beschreven. Het wordt gevormd door een theorie over technische systemen,

technische ontwerpkunde, ontwerpmethodologie en een theorie over speciale processen en systemen. De nadruk ligt hierbij op onderwerpen die bij het assembleren van produkten worden toegepast omdat mogelijk een deel van de ontwikkelingen die bij assembleren gebruikt worden, ook bij het demonteren gebruikt kunnen worden. Daarom wordt een uitgebreide analyse van het produktontwerp en assemblageproces uitgevoerd en de mogelijke toepassingen bij het demonteren worden aangegeven. Een van de conclusies van dit hoofdstuk is, dat de wijze van assembleren van het produkt een grote invloed heeft op de mogelijkheden van demonteren, en daarom op het ontwerp van demontagesystemen. Een praktijkvoorbeeld geeft aan hoe een assemblagevriendelijk produktontwerp tot een geautomatiseerd assemblagesysteem leidt.

In Hoofdstuk 4 wordt een methode voor de bepaling van de demontagestrategie afgeleid, bestaande uit drie delen: 1) bepaling van het aantal mogelijke demontageschema's, 2) bepaling van de financiële opbrengsten van iedere demontagestap en 3) bepaling een toepassing van het optimale demontageproces. Het doel hiervan is, om vanuit financieel oogpunt en binnen de grenzen van de wetgeving met betrekking tot afval, het beste demontageproces te verkrijgen. De bepaling van de demontagestrategie vormt het hoofdbestanddeel van de gehele ontwerpmethodologie. De ontwikkelde methode wordt aan de hand van een praktijkvoorbeeld toegelicht.

De systematische ontwerpmethodologie wordt in Hoofdstuk 5 beschreven. Het bevat vijf fasen die elk in een aantal stappen zijn onderverdeeld. Zowel de fasen als de stappen worden in detail beschreven en hun relatie tot de terugwinning van afgedankte goederen wordt aangegeven. Bovendien wordt de locatie van demontagesystemen in een model voor de levenscyclus van een produkt gegeven. Hierdoor worden de relaties met andere segmenten van de levenscyclus duidelijk en hun rol om tot een duurzame produktie te komen wordt benadrukt.

De toepassing van de systematische ontwermethodologie wordt in Hoofdstuk 6 beschreven. Het betreft de demontage en terugwinning van huishoudelijke apparatuur en elektronische apparatuur. De voor deze goederen ontwikkelde demontagesystemen zijn ook, tot grote tevredenheid van de gebruiker, werkelijk toegepast. Er blijkt uit, dat de ontwikkelde ontwerpmethodologie algemeen toepasbaar is voor de bepaling van de demontagestrategie en het ontwerpen van demontagesystemen. Verder worden in dit hoofdstuk nog een aantal ontwerpregels gegeven voor de ontwikkeling van demontage- en terugwinvriendelijke produkten op grond van praktijkervaringen.

In Hoofdstuk 7 kunnen tenslotte de conclusies en aanbevelingen voor nader onderzoek worden gevonden.

# Contents

## 3. The nature of design for assembly and its applicability in disassembly



## 4. Determination of a disassembly strategy

## 5. A systematic approach for the development of disassembly systems



## 6. Application of the systematic design approach

## 7. General conclusions and recommendations for further research



## Appendices

# Chapter 1

# General introduction

## 1.1 Introduction

The 1970's will be recorded in history as the decade in which the public became deeply concerned with the quality of life on earth, now and in the future. This basic interest reached issues beyond political and continental boundaries. The developed world was alarmed by the publication of the "Club of Rome" about the exhausted mineral sources, degradation of the environment, uncontrolled urban spread, etc. The aim of this club, which consisted of a number of businessmen, scientists and others, was to make clear the existing destructive tendencies in our civilization. The experimental simulation model that was developed, showed a considerable increase in the death rate as a result of energy and food shortage, and overpollution. This model implicitly expressed the consequences of continuing to equate growth with progress and neglecting recovery as an option to preserve our planet for future generations [Meadows, 1972].

The first challenge with regard to conscious manufacturing and environmental protection was made in 1987 when the World Commission on Environment and Development of the USA introduced the term *"sustainable development"*. It implies that the global environmental problems should be approached and solved now so that they are not postponed to the next generation. This concept concerns the limited usage of mineral sources, climate changes, damage to the ozone layer, extension of the deserts, air pollution, etc. These issues are also part of the second Dutch National Environmental Programme which aims to promote sustainable development in different industries on a local, national and global level [Tweede Nationaal Milieubeleidsplan, 1994]. It involves the following main aspects:

- o Closing the loop of the product life cycle.
- o Decreasing the energy usage.

- o Stimulation of product quality over product quantity.

Considering the environmental requirements for production, adjustments should be made between the requirements and the actual possibilities for fulfilling the norms in the current state of the art of the technology and economy. The economic growth should be in accordance with the environmental policy, so that less mineral sources and energy are used and less waste is generated. To achieve valuable results there is a need for a complete control of the entire product life cycle. In this context, the producers have a high impact on the above-mentioned aspects and should play a significant role in fulfilling the requirements. For this purpose, it should be made clear that a sustainable development not only involves environmental protection but also significant economic issues. Most of the activities in this field are promoted by the green organizations, customers and governments. However, there are companies that realize the benefit which can be obtained by a sustainable production strategy. In this way, a number of "environmental islands" has appeared which is the basis for a complete environmental strategy and production of sustainable products. Such a strategy is worthless if the last segment of the entire product life cycle is missing: the waste processing companies. The introduction of such firms would have many beneficial consequences for society, like the creation of new work places, utilization of the available resources, less energy consumption, improved health conditions, etc. All these attractive issues are driving our entire society into thinking about how to promote sustainable production in due time. For this purpose a drastic change in the product life cycle concept should be made. In the past this concept involved the following main stages:

- o Obtaining raw materials.
- o Transformation of raw materials into semi-materials.
- o Transformation of semi-materials into components and sub-assemblies.
- o Production and assembly of components and sub-assemblies into complete products.
- o Usage and maintenance of products.
- o Discarding products.

The recovery option is missing in this production chain. In other words, there is no effort to reuse the discarded goods and to reduce the usage of raw materials and energy for the production of new products. If this concept remains unchanged, the mineral sources will be soon exhausted and the landfills will be unable to cope with industrial and other waste. In the long run, this means that there will be no more energy sources for production and no more agricultural fields for the production of food. This will lead to a decrease in population because of the food shortage and decreasing health services. The most logical result will be the destruction of our modern society. To prevent these catastrophes, the production chain should be closed. This implies that after discarding the goods, they should not be dumped in the landfills but rather regarded as sources for energy and secondary materials. In this way, they will be returned to the primary and secondary production processes. In this view, the aim is to maximize their utilization and to decrease the amount of industrial waste. As yet we do not know how to accomplish the recovery of discarded goods and to control the production chain. However, there are workable solutions in other branches. For instance, consider water usage. After obtaining, filtering, purifying, distributing and using it, the water is not returned to its source, in this case the earth, but to the water processing company. It is possible to use it according to cascade principle: the water is used for household needs and then proceeds through various companies. After usage it does not have the same characteristics as it had when it was obtained from the source. The water is polluted and it is not suitable for usage in this condition. However, the water used already is not regarded as waste but as a source for the water processing company. After application of various purification processes, the water can be cleaned up so that it will have the same characteristics as the original source. In other words, the water circulates in a closed production chain, saving mineral sources and limiting the environmental pollution. Similar considerations can be made with regard to the production of industrial products. The aim is to create sustainable production facilities so that the industrial products can circulate in the same closed chain as the water.

In addition, the production costs of a firm are calculated without considering the recovery issue. Also the logistics, marketing, finance, economics and other aspects are considered from the same view point. All efforts to decrease costs and reduce pollution have been aimed at the products up to the point they are shipped to the customers. The responsibility of the producer for his goods was limited to the product warranty. The environmental and economic importance of recovery and utilization of discarded industrial products have not been recognized. This has resulted in enormous problems for society, which will have to be solved now and in the coming years because of two main reasons:

1) The enormous environmental pollution.
2) The limited mineral and energy resources.

To be able to understand and approach these significant issues, people must change their normal perception concerning the product life cycle and consider the recovery problem. This implies the reuse of discarded products that will close the life cycle chain and reduce the environmental impact and production costs.

Considering issues related to the reuse of industrial products will lead to significant changes in the marketing, economy, development, production, distribution, usage, maintenance, etc. Moreover, many new stages and aspects will occur, resulting in a new life cycle concept that involves the recovery issue. This concept can not be developed at once or by a single institution. For this purpose the effort of all members of society are required to make this concept workable.

The first steps towards promoting activities associated with the recovery of materials and products are being taken by the governments of some industrialized countries. They are trying to reduce the environmental impact of products during their entire life cycle. Because of overpollution and consumption the landfills are reaching their permitted capacity. In addition, society is against opening new waste facilities. Although municipal solid waste is the most obvious result of our society, industrial waste streams are much larger and cause more serious problems. While the management of the municipal solid waste is a well-known problem and many actions have been taken to reduce it, there is no workable strategy for dealing with industrial waste yet. Most of the current activities associated with the reuse of discarded durable and consumer products are imposed by legislation. For instance, the Dutch government is striving to reduce the amount of waste and to remove poisonous materials without damaging the environment [Blonk, 1993]. These objectives can be realized by developing and implementing new legislation rules so that companies will be compelled to consider the following items:

- Avoiding the creation of waste and pollution during production and consumption.
- Reducing the unavoidable waste generated as much as possible by reprocessing the product discarded flow.
- Creating a secondary market for the obtained materials and products during reprocessing.
- Removing the waste with a negligible risk to the environment where incineration with energy recovery has the priority.

To execute this strategy, the following main goals have been established:

1. Prevention
   * Maximizing quantitative prevention.
   * Maximizing qualitative prevention.
2. Collection
   * A differentiated collection of 100% of the electronic consumer products by the year 2000 to obtain optimal processing with regard to the environment.
3. Product reuse
   * Maximizing product reuse.
4. Material reuse
   * Realizing the most urgent material reuse.
   * Realization of the following tasks with regard to material reuse by the year 2000:
     - 90% material reuse for household appliances.
     - 70% material reuse for electronic consumer products and other appliances.
5. Remnant processing
   * Only to take place by integral incineration if:
     - The amount of environmentally harmful materials in the waste are negligibly small.
     - A relevant volume reduction is obtained [BDE, 1994].

This kind of regulation is not only being considered in the Netherlands, other countries have some similar ideas. One of the forerunners with regard to this problem was Germany. The German government wants to make the manufacturers and importers responsible for the discarded phase of products. For this purpose, in July 1992, a bill was proposed called "Elektronikschrott Verordnung" [Angerer, 1993]. It includes a manufacturer-oriented collection and reprocessing duty for manufacturers and importers of all electric and electronic apparatus. Following the time table, this bill should have been operational in 1994 but this has not been the case up to now. The German government aims to extort an integral concept for discarded electric and electronic products by this bill. Such an integral concept includes the following steps:

- o Logistics for collection and transport.
- o Disassembly (dismantling) of apparatus.
- o Reuse of components and recycling of secondary raw materials.
- o Selling secondary raw materials to the market.

However, the key to saving nature is to bring environmental care to producers. For this purpose they should be convinced that designing 'green' products also means designing for the generation of more profit. Before the manufacturers are completely aware about the advantages of developing 'green' products, the current stream of discarded products must be processed. This requires the development of disassembly networks and plants that are able to tackle this issue. With regard to complex durable and consumer products, recovery of both valuable and harmful materials and components can only be achieved by means of disassembly. This process is becoming a major topic in the strategy for reducing the environmental impact of industrial waste.

## 1.2 Some disassembly and recovery issues

In the last decade the stream of durable and consumer goods that are discarded by the customers has become tremendous. This huge number of out-of-life-cycle products asked for a completely different approach with respect to their recycling and disposal. The goods, which are available for recycling at the present moment, were produced about 15 to 20 years ago. At that time, *no considerations were made concerning their further reuse.* The absence of such considerations causes enormous environmental problems as well as the loss of value added to products and materials that can be reused for different purposes. For example, the gross electronic waste in Germany has a volume of more than 800,000 [tons/year]. The numbers and types of major electric appliances in use in Germans households in 1990 and the resulting volume of waste and materials composition to be expected from washing machines in the near future are shown in Figure 1.1. As can be seen, there are a lot of value added components and materials that can be extracted from the discarded durable goods (washing machines) and reused again. This example only shows the expected colossal stream of abandoned washing machines, but there are many other goods that are waiting to be disposed of as well. There are about 1.5 millions cars retired from exploitation every year in U.K. In the Netherlands about 600,000 refrigerators and freezers are rejected by the customers per year [Coolrec, 1993]. These facts and data give a very limited impression about the seriousness of the entire problem. In addition, there are materials that cause enormous damage to the environment.

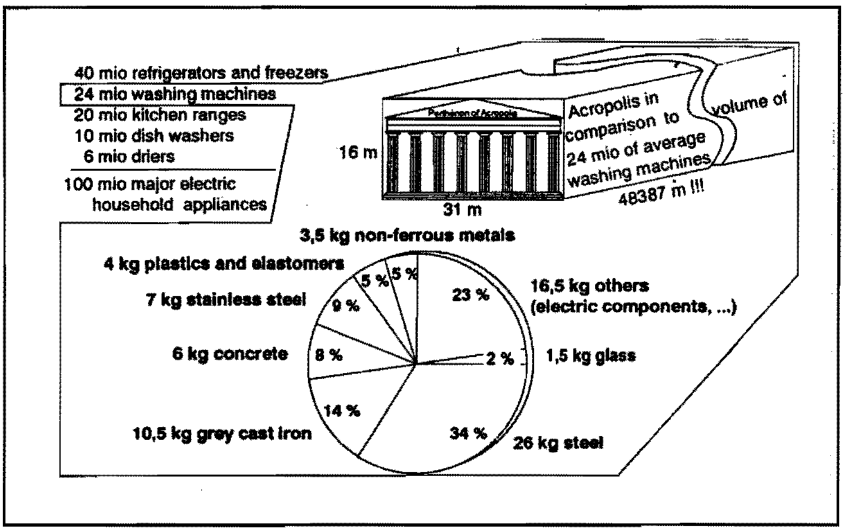



Figure 1.1: Main types goods in usage in Germany [Hentschel, 1993].

Furthermore, the resistance of the "green" organizations is increasing, claiming that the enterprises must be responsible for the recycling and disposal of their own products. The legislation in some industrialized countries is driving the companies to think about the entire product life cycle. Since landfills are already limited, prices for shredding residues from used cars have increased from about 20 DM per ton to 600 DM in Germany in 1992 [Ashley, 1993]. In the very near future many companies will be compelled to take back their products after the consumer has discarded them. For instance, the German government has already required that car companies get back products they manufactured at the end of the car's life and reuse their materials in a proper way. In other words, every enterprise will have to consider the environmental issues in order to survive and to be competitive in the international market. These new considerations should become a policy of every firm and individual, which should be aware of the benefit of efforts spent on objectives with an environmental focus.

However, there are many arguments against recycling, because it is not considered feasible in some branches. The question of interest is, whether the sum of all costs, associated with the reuse of products and materials, are smaller than the value added to materials and parts obtained from the recycled products. An important question that should be resolved, in an optimal recycling strategy, is the degree of disassembly that is efficient. The benefits of disassembly, which is usually labour intensive, depends on many factors.

Why is the risk of recycling so high? Why is the majority of industrial enterprises hesitating and do they not spend time on this important issue?

The answer to these significant questions can be found in the problem's background. At present the firms have to recycle goods that have been designed and produced a long time ago. This fact brings along the following problems:

- There is no clear product specification available anymore.
- There is a lack of information about:
  - What materials have been used.
  - Part identification.
  - Product variety.
  - What joints have been used to accomplish the entire product structure.
  - What is the quality of the current parts and materials within the entire product.
  - How many parts have been replaced during the product life cycle and what is their added value at present.
- The old durable goods were not designed to be disassembled easily and efficiently.
- It is difficult to determine the expenses for the recycling of old-fashioned products.
- How and where the discarded products can be collected for further recycling:
  - Unbalanced orders.
  - Uncertain logistics.
  - Fluctuation of the disassembling cycle time.

In Figure 1.2 some arguments about disassembly and reuse of discarded goods are depicted. As can be seen there are some reasonable arguments against disassembly. But the number of positive ones must also be deliberated. First of all, some value added to materials can be extracted with profit even from old durable and consumer goods. They can be reused in the current manufacturing process saving a number of components and decreasing production costs. Others can be recycled and introduced in a number of different production processes. In addition, firms that produce "green products" will have a certain advantage in comparison with their competitors in the international market. They will have lower production expenses as well as lower environmental taxes for disposal, which must be paid according to the legislation. Furthermore, thinking now about recycling and the disassembly of the abandoned goods means creative potential for future design and a strategic advantage in future profitable markets.

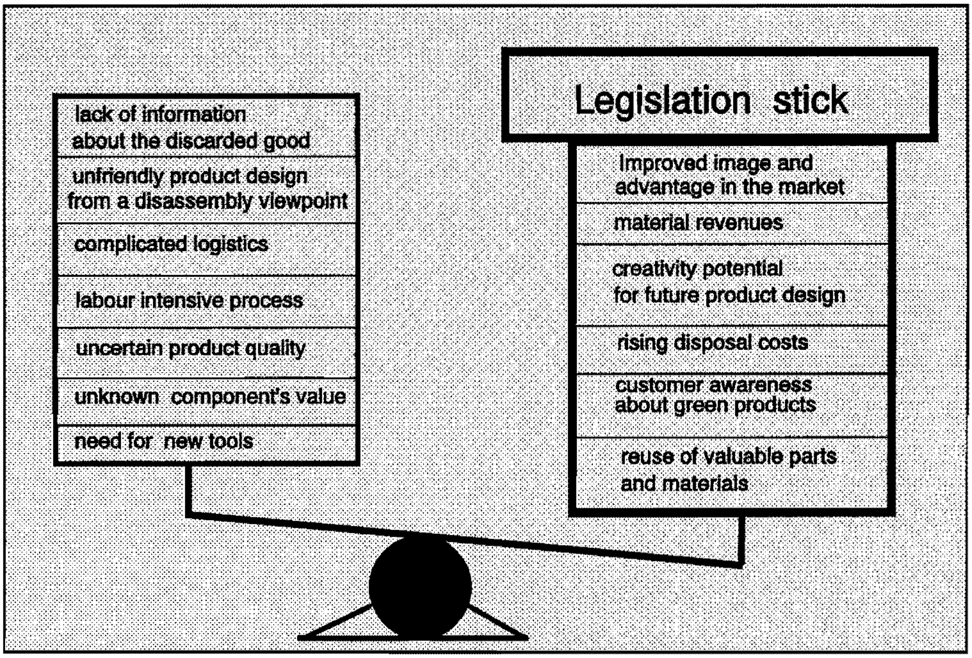



Figure 1.2: Some disassembly issues.

Some firms have already looked into various aspects of disassembly. The efforts are used to solve single problems without paying attention to the entire issue. This leads to unreliable disassembly activities, which in the most cases achieve unattractive results and discourage companies from proceeding further. There is a need for a comprehensive disassembly strategy concerning the recovery of industrial goods. This new concept will be totally different in comparison with the workable solutions for solid waste management. To accomplish the recovery of discarded goods, a number of disassembly factories should be introduced. This requires the development of a comprehensive disassembly model and a systematic approach for the design of disassembly systems.

## 1.3 Main industrial engineering aspects of disassembly and recovery

As a result of the governmental rules, the treatment of discarded goods not only became an environmental problem but also a company or management concern. In other words, the producers should organize their facilities in such a way that they will be able to process the industrial waste flow. In the near future, company managers should concentrate on issues after the products has left the factory; they should manage the complete production chain including disassembly and recovery issues. This implies that the firm's results and performance are influenced by the recycling policy and treatment of discarded goods. This involves a number of industrial management problems, which should be considered when processing discarded goods. They will be described in order to give insight into the recycling issue.

### 1.3.1 Product design

There is no doubt that one must start tackling this problem now although the disassembly process may be not profitable at first. It is evident that the recycling aspects of the future products should be considered in the early product design stage. The product development aspects are given in Figure 1.3. One can see that the new environmental aspect influences the requirements as well as the product's image. Since the introduction of new products always begins with a specific market need, the prediction is that recyclable products will be desirable in the international market.

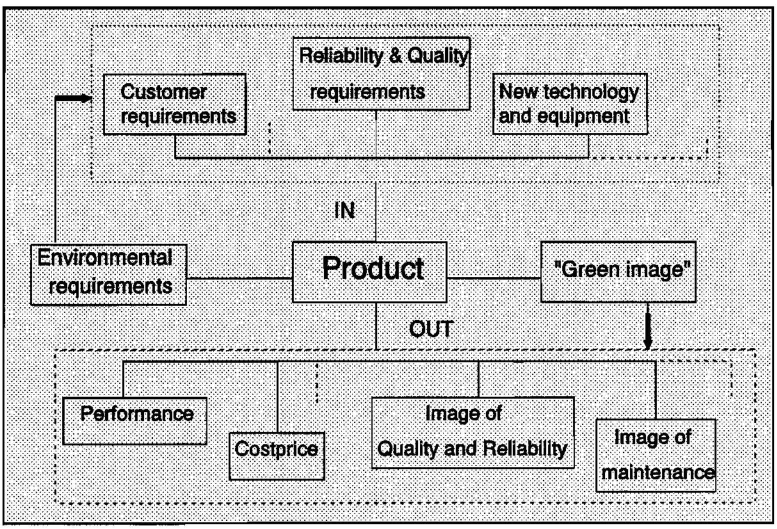



Figure 1.3: Some product design aspects.

In the USA 80% of the clients accepted the additional costs that had to be paid for environmental protection in 1989; 15% were against this idea, which is less than in 1981 when 40% did not accept this proposal [Anonymous, 1990]. Industrial consumers are increasingly requesting that the goods and semi-products that they buy should be environmentally friendly. For example, McDonald strongly supports its agricultural suppliers to use biologically safe non-toxic insecticides. L'Oreal, the producer of French cosmetics, has replaced the CFCs in its sprays by non-ozone consuming substitutes due to the enormous pressure from some leading European retailers. Some car companies in Germany are insisting that the suppliers should produce parts and components that are recyclable. In other words, at present the customer is requesting enterprises to produce environmentally friendly products. With reference to this fact, the old interpretation concerning the shorter life cycle of a product and the limited pay-back period should be changed. In the future the technological developments will be implemented more quickly and they should be combined with a complete product life cycle including recovery after usage.

In general, the existence of a product begins because of a market requirement. It does not end when the product is sold, but rather when it is *recycled and disposed.* This assumption changes the ordinary understandings about product life cycle. In other words, the environmental requirements should be converted into a successful product design within *concurrent engineering* which is defined as: *a systematic approach to the integral concurrent design of products and their related processes, including manufacture and support.* This approach is intended to cause the developers from the outset to consider all elements of the *product life cycle from conception through disposal*, including quality, cost, schedule, produceability, user requirements, service and environmental aspects [Constance, 1992]. This means, that the total process of design and development should be executed while considering this new issue. Hereby, all appropriate tools available for successful and simultaneous design can be used. The problem, how to design with respect to the new environmental requirements, should be approached comprehensively and in a systematic way.

For instance, to determine the requirements of the customer and to convert them into a "green" product design, a QFD (Quality Function Deployment) tool can be introduced [Hauser, 1988; Bossert, 1991; Hemel, 1995]. The target is to include the environmental aspects in the early stage of the product design, which will result in more attractive products. QFD is a management tool for successful development. The method is based on the firm belief that the design of any product or system should satisfy a specific need, which is mostly related to the client requirements; the legislation requirements are regarded in the case of recycling. The "voice of the customer" is deployed at each phase of the product planning, design, manufacturing, marketing and recycling. It is clear that design engineers, manufacturing staff, marketing people, etc, should work together closely and address all relevant issues simultaneously. One of the key benefits of QFD, that can be used for the purpose of this investigation, is a better understanding of customers and legislation requirements and the transfer of this information to the design process. The method can not only be used for the design of a product but also for the design of a disassembly system. QFD consists of a number of charts that represent WHAT needs to be achieved and HOW it should be done. By means of a cascade of several charts, the voice of the customer is continuously and quickly introduced into the design, production process and reuse of the products. Following the development of the charts, the corresponding disassembly process and system for any product can be introduced. This integral design consideration is a new step in concurrent engineering. As can be seen from Figure 1.4, the process is a closed circle. It begins from the market and ends there again, but this time including the recovery aspects in all stages.

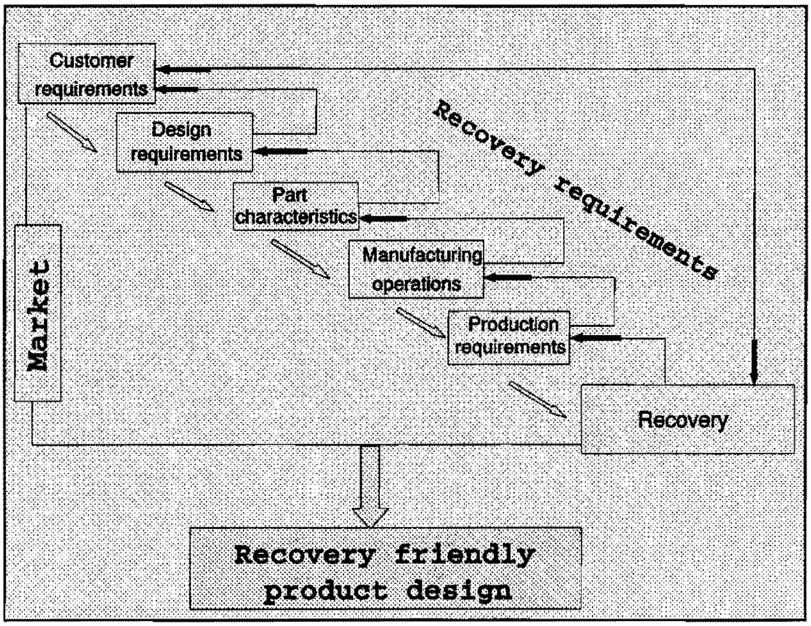


Figure 1.4: QFD for recovery issues.

Apparently concurrent engineering should be applied in the beginning of the product life cycle, because it is useless in its end. This is the reason that the products designed today should be considered from this integral point of view [Beitz, 1993]. Disassembly and recovery of the discarded goods means a gain in creativity for a future product design. The experience obtained from disassembly and recovery activities can be used in the design of the follow-up products. This fact explains and justifies the introduction of disassembly systems for discarded products.

### 1.3.2 Information

One of the most serious problems associated with the recycling and recovering of materials is the lack of information. In this context, it is very difficult to determine the value of products and materials of the discarded goods. This fact gives an unclear idea about how to approach the problem and to what extent one should proceed with disassembly and recycling. In many cases, the number and type of materials is not known at all, hence, their market value can not be determined. Furthermore, as a result of the lack of information, it is impossible to judge the abandoned goods' quality. As one can see the problems related to the lack of information are enormous and often they are very reasonable arguments against recycling. This is the reason that every designer must include a way to provide sufficient information in his design strategy that will facilitate the recycling later on. It is clear that the products and materials must be identified by the designer in the early stages of the process, and they should be easily recognized when one has to recover and reuse them. In addition, it is necessary to track the quality of valuable parts in a product in every stage of its life cycle. At the moment the identification of plastic materials is performed by means of special infra-red equipment, which is very expensive and requires a lot of time. In addition, the quality of the parts and materials should be known in every product life cycle's stage.

Some producers have already tackled the above discussed problems. For instance, GE Plastics has developed an electric kettle that is fully recyclable. In this product every material has a special name and number, which can be found in the inner side of the components. The location of this information facilitates the identification process [Remich, 1991]. The company to be engaged with recycling of such products will execute this process with limited efforts and costs, because of the proper product design.

IBM faces the information problem with the development of a material-code-system, which should result in an comprehensive international standard [Bergstrom, 1991]. The firm has introduced a triangular green symbol that can be molded together with the corresponding number in every plastic material. During the recycling process the choice and separation of valuable materials will be simplified. When every designer is aware of the necessity of this approach and introduces it in his design process, the recovery of discarded goods will become a profitable activity.

### 1.3.3 Marketing aspects of recovery

The marketing research aims the establishment of information links between the producer and the customer [Churchill, 1988]. In the case of recycling this emphasizes the link between the recycling companies and the potential customers for the recycled goods and materials. In other words, the marketing aspect involves the specification of what information is needed, the collection and analysis of the information and the interpretation of that information with respect to the goals that should be achieved. While considering the recycling of discarded goods, the managers should adopt a recycling goal and should consider a longer product life cycle. The aim of the marketing managers will be related to the area of:

* Providing sufficient and significant information about the products and materials being produced.

The information about products can not only be supported by expensive advertisements. The potential customer will demand more specific information. The marketing will not only be limited to information concerning the advantages of the product. Moreover, the personnel of the marketing department should be aware what kind of products they sell and what their important features are.

* Encouraging the collection of discarded products.

To promote and to make recycling a reality, a system for collection of comprehensive information should be developed. The marketing department should attract the customer's attention if distinctive data are required concerning the products that are in exploitation.

* The development of a new sales concept.

The recycling and reuse of products implies that a secondary market should be created for specific products. Hereby, the marketing principles are the same as for the primary one. Another important item that should be further investigated and developed concerns the way products are sold in the market. One proposal is that in the near future the customer will not buy products but will lend them from the producer. The client will be obliged to pay particular taxes for using the product and return it to the company after a determined period. The product's price, the period for use, etc., will be set down in a contract. In this case the producer will remain the owner of his goods, and will be responsible for their recycling and reuse. All expenses related to these activities will be covered by the producer. In this way, the firm's profit will no longer be determined by selling as many products as possible, but rather by the product's quality, reliability and recyclability. The sum of taxes that should be paid by the client will not only contain the expenses for using the product, but also the extra efforts being made for the design of recyclable goods. This suggestion about the future sale of products will completely change the firms' goals, pushing them to consider recycling and reuse as very significant issues.

### 1.3.4 Logistical aspects of recovery

Concerning the reuse and recycling of products, components and materials, the following aspects are important from a logistical viewpoint :

- o Duration and frequency of discarded goods transportation.
- o Quantity.
- o Quality.

There are a number of ways to influence the moment that the product is discarded. For instance, the firm can give an attractive price to customers that bring back their discarded goods on time. On the other hand, the producer can ask the client to return the old products as a requirement for selling him new ones (for example, the customer can buy only new bottles if he has returned the old empty ones).

The irregular distribution of abandoned products should not be a problem for the recycling company. The distribution can be organized in such a way that the products will be delivered in batches and will not cause obstacles for the recycling firm. In this way they can be supplied on time if there is a specific order.

The prediction of the discarded product's quality, which is offered for recycling, is more difficult than the prediction of the exact time of delivery. On the other hand, the discarded good's quality can be reasonably determined in the collection place. There the discarded products should be checked and sorted according to their quality. The problems are the same as those related to natural materials such as milk, meat [Duvall and Hoffman, 1983], fish [Duncan, 1983], fruits and also integrated circuits manufacturers with regard to the wafers [Campbell, 1988]. The variety of discarded product's quality can be limited by introducing selective collection. One rule that could influence the quality is that a certain price will be paid for those discarded products which fulfil determined requirements. Another way of doing this is by taking the worst product's quality for calculation of all recycling expenses. For instance, the duration of glass melting depends on the most polluted goods. The same is valid for the cleaning of old bottles, whereby the most polluted ones can be taken as a start point. This approach assumes higher expenses for recycling than the actual ones.

Another aspect concerns the internal logistics. In the assembly process the materials and components are joined together till the entire products structure is accomplished. While executing the disassembly of a product more materials streams will appear. They should be transported and stored in a particular way. Collecting materials in huge quantities is recommended, in this way, the price obtained is higher while the transport costs are reduced. This fact means one has to pay special attention to the storage and conservational facilities.

### 1.3.5 Economy and performance measures

The reuse of discarded goods, parts and materials will influence the initial financial viewpoint, thus making reconsideration possible. The producer must include costs being made for recycling and reuse in the total cost. He will be pushed to take into account these additional expenses since they will become lower than the costs of dumping discarded materials in the landfill. McDonalds has experienced this fact in Germany [Vandermerwe, 1991]. The expenses for the dumping of one ton garbage were 220 DM, while the costs for recycling and reuse of the same quantity were only 100 DM. Prices for shredding residues from used cars have also increased as was already mentioned. It is expected that soon all industries will be affected by the enormous increase of taxes for the storage of waste. This means that every company should take measures to minimize the amount of waste, which in turn should decrease the total production costs.

In addition, there are many supporters for a new economic model that should include the costs of environmental damage. According to this new approach the economists and managers should have a broader view concerning the production. The firm's progress and profit are not the only issues anymore. The most important one is to create a healthy production without environmental damage. In this, the method of full cost accounting should be introduced, which includes the consequences of ecological damage in the total production cost. The air, water and land will no longer be used freely. The actual environmental costs being made during the production, usage, recycling, reuse and dumping will be taken into account and introduced for the estimation of the total costs. The consequences of such a calculation are enormous. Popoff and Buzzelli (1993) assume that most of the agricultural companies will disappear if the complete costs for water usage are calculated according to this method.

Another approach is known in practice as "leasing". In this case, we regard the leasing as a contract between the producer (lessor) and the customer (lessee); there is no third party (bank) involved. The lessee obtains the right to use the leased asset but not to own it, as this is the case with a purchase. In other words, the customers can only purchase the product's functions and can use them according to determined conditions (contract). After the contract expires, the customer is obliged to return the product to the firm-producer, which has final responsibility for its recycling and reuse. By the introduction of such an approach the recovering of materials and goods can be facilitated, which would result in a significant cost reduction. If the products are leased, the producer can use more expensive materials with a higher quality. He will be sure that the materials will be returned and that they can be reused according to their quality. The aim is to improve the total performance of the products. For instance, the influence of a computer's vibration can be decreased by introducing gold-framed contacts. According to current practice, this approach would make the price extremely high. But if the producer is sure that the gold will be returned, then he has to consider the cost only for reuse. In this way, high quality products can be produced and delivered without a significant price increase. The concept of leasing is represented in Figure 1.5.

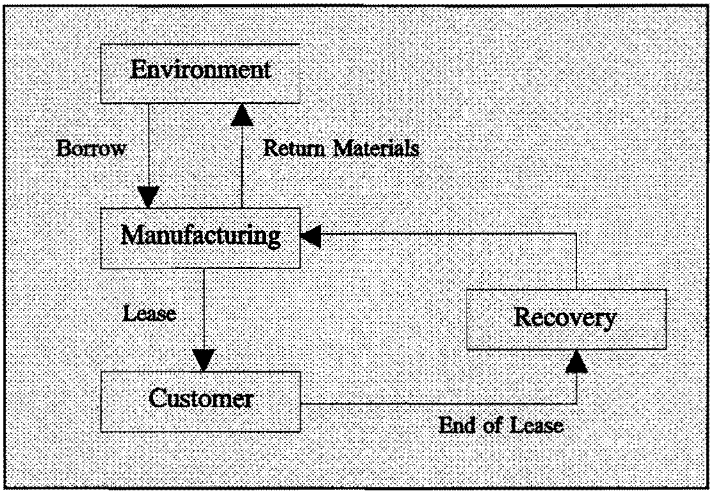



Figure 1.5: Leasing of products [Navinchandra, 1993].

Another aspect that should be considered is that after the first usage, the products can be sold to a secondary market. There will be a need for such products with reasonable quality but with a lower price. The new goods that are produced according to the latest advanced technologies can be offered to a very limited number of customers. This fact justifies the strategy for the development of secondary market. Here the products that are approximately in the second phase of their life cycle will be sold. They will be discarded by the first clients because the last ones always want to purchase the state of the art products. At present the abandoned but still functioning products can be sold to a second group of customers and so on. When the producer sells products to the market he loses all the efforts and capital investments being made for their production. There is no way to reuse the investments again. If the product is leased then the producer is ensured that the products will return to him and he can gain revenues to some possible extent [Navinchandra, 1993]. In this way, by including the recycling aspects in the early design, an additional profit can be generated by selling goods to the secondary market.

Concerning the recycling and reuse of discarded goods, parts and materials, it is very important to judge how much money and energy should be invested for the execution of this process. In reference to this, the following important items should be considered:

- Some units are more valuable than the sum of their components.
- Not all parts can be reused.

- o In some particular cases, the recycling of discarded goods can cause more environmental damage than if they are dumped or burned.
- o Poisonous parts and materials should be removed and processed in an environmentally friendly way before they are sent for dumping, burning or reuse.

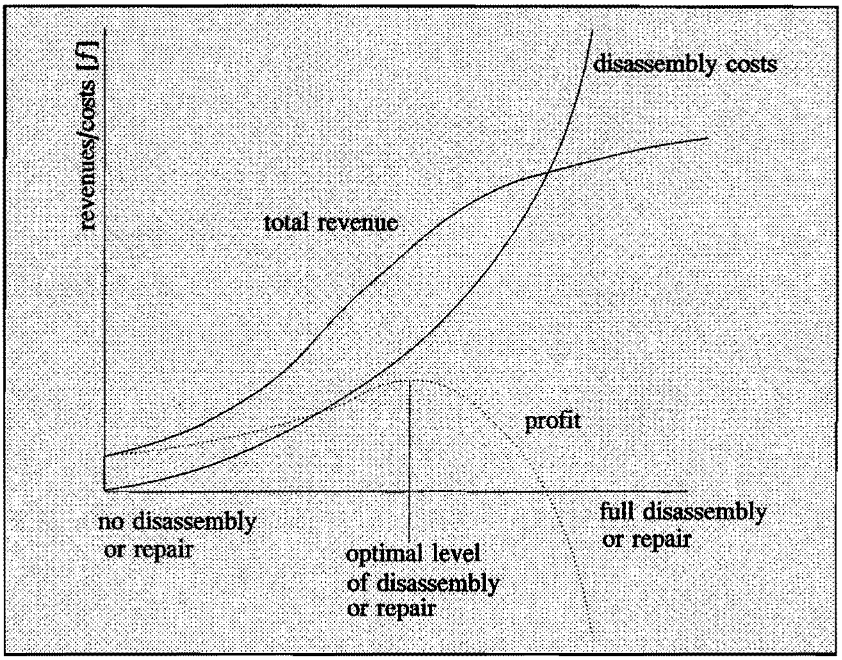


Figure 1.6: Disassembly costs [Navinchandra, 1993].

Figure 1.6 clarifies the item discussed above. It can be seen that the costs for reuse and recycling increase when the level of recycling increases. At a defined level, profit does not rise anymore. The optimal level of recovering can be achieved where the profit is maximal. This stage is different for every product and it should be determined for every particular case. This figure only gives the financial quantities. The environmental requirements are not involved in this model. In addition, the disassembly curve starts from zero, which means that the capital costs are not included. There is doubt whether the same graphic can be observed in practice; this will be clarified after we have looked at the results from practical work.

### 1.3.6 Assembly and disassembly

With the introduction of an assembly line for automobiles in the early 1900s, a new phase in mechanization was introduced. For many years the assembly process was being developed, which not only resulted in automation of the transport and handling operations, but also automation of the control of assembly machines and their operations. Later on, when the first robot appeared, it became easier to integrate the material handling with the automated assembly of products. For this purpose various methods for analyzing a product, its redesign and design for ease of assembly were developed. With the introduction of computers, software packages became available for accountancy, product analysis, materials and production planning. All these activities led to the development of easily assembled products, advanced assembly processes and the corresponding flexible automated assembly systems.

Considering this long evolution of assembly it is unrealistic to think that disassembly can be improved at once to the level of assembly. However, it should be understood that these two processes are similar and complement each other. Therefore, their common and particular features should be clearly distinguished and investigated. This allows us to reduce the effort for the development of an advanced disassembly process by following procedures that have already been introduced, and can be applied to both processes. While facilitating disassembly with all the knowledge and experience available in assembly, new particular disassembly aspects should be investigated and their importance clarified. The utilization of this approach will make the development possible of advanced disassembly processes and systems in due time. Since this issue is significant for the execution of disassembly, particular attention to this subject will be devoted in the following chapters of this dissertation.

## 1.4 Disassembly systems: transformation of materials

The concept of a system is widely used in almost every area of human experience. Systems are defined as a finite set of elements collected to form a whole under certain well-defined rules, whereby certain definite relationships exist between the elements, and its environment [Hubka, 1988]. There are several types of systems: production systems, assembly systems, control systems, ecosystems, transport systems, weapon systems, etc. A technical production system is defined as a collection of singular, sequential and/or parallel transformation processes, which are related by a structure of interactions. They are organized and controlled to allow the system to produce industrial products [Sanders, 1988]. The most important property of every technical production system is that it transforms inputs into desired outputs. Moreover, it transforms inputs into more valuable outputs. Based on the above, a technical production system is defined as: "*a transformation process which transforms inputs into outputs; at least one of the outputs is desired and has an added value compared to its input*" [de Ron, 1994]. A necessary condition to accomplish of this transformation is the availability of energy and information.

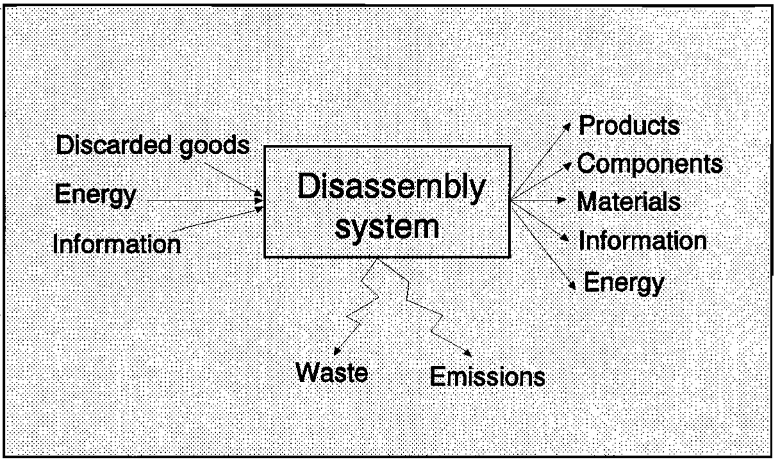



Figure 1.7: A black box model of a disassembly system.

A disassembly system can be also regarded as a type of a technical production system, see Figure 1.7. Thus, the above definition can be applied with a small modification to a disassembly system too. For a disassembly system, the input consists of a variety of discarded goods that contain the compounded input materials. The difference with a technical production and assembly system is obvious where the input is the raw materials and semi-materials. Regarding disassembly systems it should be clear that the inputs can not be chosen; they are fixed in the compounded materials. Moreover, the variety and the time schedule of the input can hardly be predicted. On an abstract level, an analogy can be made between a disassembly transformation process and milk production where the input is raw milk. The outputs are a number of products: butter, yoghurt, margarine, etc., which depend upon the market demands. In the same way, a disassembly system should transform the compounded materials into a number of products: ferrous, non-ferrous, plastics, copper, etc. This requires the development of flexible disassembly systems that are able to process a wide range of discarded goods in view of the current market demands in the coming 10-15 years. The input of compounded materials (discarded goods) are transformed by the disassembly systems into outputs that are products of the transformation system. The output products are the separated materials, components or sub-assemblies that are obtained, which can be reused for various purposes. Therefore they have an added value compared to the input compounded materials. The undesired output is waste which should be minimized and should cause as little environmental damage as possible.

The transformation process in a disassembly system can be divided into three main sub-processes:

- Separation of components and materials by means of disassembly.
- Shredding of components.
- Separation of material flows after shredding.

Every step has an exact purpose that will be clarified in the following sections. After the execution of these processes, the following production streams may appear :

- Useable components.
- Ferrous materials.
- Non-ferrous materials.
- Pure plastics materials.
- Mixed plastics materials.
- Cables.
- Glass.
- Fluids.
- Poisonous waste.
- Non-poisonous waste.

The choice what stage should be executed and what output should be obtained depends upon industrial engineering considerations such as the economic, technical and environmental aspects, which have priority above the others. These issues will be further treated in detail.

## 1.5 Terminology and definitions in recovery

In the literature most of the activities concerning the recovery and reuse of goods and materials are associated with *recycling*. This is a very common expression and it comprises a lot of different aspects. In order to establish a clear terminology and to use the various terms in a proper way they have to be defined according to their exact meaning, as they will be used in this research.

Referring to the literature a comprehensive description of the terminology in the field of recycling could not be found. The reason is that it is a relatively new item and some terms have not yet been clearly defined. For a sense of consistency we will make use of some of the most important definitions found in the literature. They will be stated from the viewpoint used to approach this problem.

What is recycling actually ? Is it the same as reuse? And what is our perception of disassembly and dismantling? Do they have the same meaning? Is disassembly just the reverse process of assembly? In the literature, the following definitions are offered [Parker, 1994]:

o **Recycling** - *The extraction and recovery of valuable materials from scrap or other discarded materials.*

o **Disassemble** - *To take apart into constituent parts.*

The above definitions are very general. In this context, recycling concerns all kinds of valuable materials and their recovery by means of various processes. *In the current research we focus on the recovery and reuse of semi-products or materials from durable or consumer goods, which have been produced in discrete production.* The extraction of these valuable semi-products and materials, for further processing and reuse, can be achieved by applying disassembly and dismantling operations. In this way, the constituent valuable parts are extracted from the entire product. The intention is to first execute disassembly operations that will not damage the product and do not pollute the environment. Disassembly should be applied if it is feasible and it is necessary for a particular part to be obtained without damage. If these two conditions are not valid then other processes should be introduced.

In this research disassembly often is used a as common term that comprises all activities associated with the reuse of discarded products and materials, such as the collection of abandoned goods, distribution, service, disassembling, dismantling, remanufacturing, recycling and disposal. Each of these terms only covers certain features from the entire disassembly. In fact, these are product recovery options applied after the products have been abandoned by the customers. They are meant to close the loop of the product life cycle. Besides the use as a common term, disassembly represents a product recovery option and in this view its meaning is close to the definition already given. In addition, disassembly systems are technical means by which the entire recovery process is accomplished. In consideration of the issues that play a role in this research, the following definitions are used:

o **Recovery (general)** - Organization and execution of all activities associated with the reuse of discarded durable and consumer goods and materials.

- **Disassembly (process)** - To take apart products into constituent parts by means of various operations so that the obtained components are not broken and/or damaged.

- **Repair** - Recovering the functions of a good during its exploitation but before it is discarded.

- **Test** - Execution of control operations that determine the quality of a product and the functionality of its elements.

- **Remanufacturing** - Bringing used products up to quality standards that are as rigorous as those for new products; it differs from **reverse manufacturing** used to express solutions to maintain a system for a longer period of time [Ingle, 1994].

- **Refurbishing** - Improving the quality of discarded goods to quality standards that are less rigorous than those for new products.

- **Service** - Recovering the product functions by means of replacing failed components after the product has been abandoned by the customers.

- **Dismantling** - To take apart into constituent and destroyed parts by demolishing the products elements.

- **Recycling** - To reuse materials from used products and components after disassembly has already been applied.

- **Disposal** - Disposing of products and materials that can not be reused for any purpose and do not damage the environment.

- **Discarded goods** - Products that are rejected by the customers because they do not need them for any reason; they contain compounded materials that are used as input in disassembly systems.

- **Disassembly process (system)** - A transformation process that transforms inputs (discarded goods) into outputs (products); every output has an added value compared to its input or should minimize the environmental impact.

- o **Product life cycle chain** - Extension of the ordinary concept with reuse of products and their disposal.

- o **Sustainable products** - The products are designed for the total life cycle, as they are produced, distributed, used, disassembled, reused and disposed of with a minimal environmental impact and use of resources.

- o **Flexible disassembly systems** - Systems that are able to process a wide range of discarded goods now and in the future.

- o **Disassembly strategy** - It gives a clear and comprehensive plan for the recovery of discarded goods.

As regard these definitions, the reader will understand their exact meaning for the purpose of this research. The difference between repair and service can be seen as they represent activities in different stages of the product life cycle. In addition, the dissimilarity between disassembly and dismantling is obvious, as the second operation is less precise and implies the use of destructive methods. To summarize the definitions the following statement should be kept in mind. *Recovery is a general term that comprises all possible ways to recover and reuse durable and consumer goods.* The other activities are only means by which the entire recovery process can be accomplished. Concerning the scope of this research the above definitions have been introduced to serve the topic under consideration at most.

## 1.6 The objectives of the research

The main objective of this research is to support the current and future developments in the field of disassembly and reuse of discarded goods and materials. One of the important steps towards achieving this goal is the execution of a comprehensive literature study in order to determine what the actual problems are and what should be done in due course. As was mentioned before, the legislation rules and other factors are pushing companies to consider the product recovery option and to develop facilities for processing the increasing stream of discarded goods. In this view, the requirements introduced by the legislation are not the same for all products. The most severe demands are made on goods with a high environmental impact. The expectation is that new rules will follow for environmentally friendly production and reuse of a wide range of products. This means that every producer should consider his role as a part of the sustainable production chain.

For this purpose, a comprehensive disassembly model should be created. It should represent the complete production chain according to the concept of "sustainable production". In this model, all segments of the entire product life cycle should be made clear including the recovery option. In addition, it should give information about the flow of materials, energy and information, and the responsibility of every company for its successful implementation. Once this has been accomplished, the role of disassembly systems as an indispensable segment of the entire product life cycle will become clear.

The next stage is the design and implementation of disassembly systems as a way to reuse discarded goods and materials. This is a complicated management task that comprises various issues. First, disassembly systems should be developed in accordance with legislation rules and should achieve desirable economic and environmental objectives. There are many constraints that have to be tackled during system development, like the marketing pull, information available, technology level and logistical structure available. In other words, the aim is to determine the most attractive goods to be disassembled and reused at that time. Such products should have a high economic and environmental impact. Therefore a choice should be made among various types of discarded goods. For instance, a preference can be given to refrigerators over electrical shavers, because of the higher environmental impact they have if they are dumped and the number of materials that can be reused. This thesis deals with the disassembly and reuse of discarded goods produced in the discrete production. It does not concern goods or materials from other branches, or the recycling of municipal solid waste. More precisely, the efforts are concentrated on the processing of consumer electronics and household goods, which represent a large percentage of the discarded goods. The aim is to cover issues for which there are insufficient data and to use the experience to recover similar types of consumer and durable goods. In general, the discarded goods should be disassembled and reused by the most efficient and economic disassembly systems. This implies that a disassembly strategy should be established that accomplishes this goal. A disassembly strategy involves the generation of the optimal disassembly operations and level; it is based on economic and legislation requirements.

After the type of discarded good for disassembly and the optimum process have been determined, the design and implementation of the corresponding disassembly system follow. This is a complicated issue that requires special skills and knowledge. The systematic development, choice and implementation of disassembly systems from an industrial engineering viewpoint is described in this dissertation. *It gives a comprehensive procedure on how to design disassembly systems that process discarded goods in the next 10 - 15 years.* This period is regarded as the first recycling phase (1) where the products are not designed for disassembly and recovery, see Figure 1.8. The following phase (2) represents the increase of recyclability due to the improved design, which facilitates the disassembly process. In the last phase (3), sustainable products are disassembled, which implies high recyclability and less environmental damage. In addition, the most feasible system configuration should be specified for the goods under consideration.

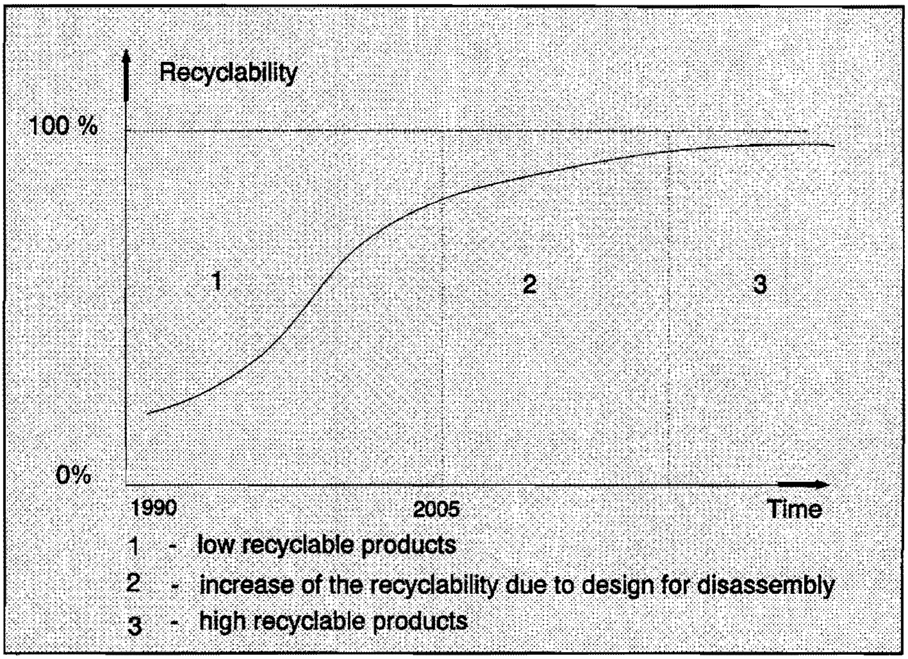


Figure 1.8: Recovery phases of discarded goods.

The development of the current disassembly systems should be based on the current technologies; no considerations are made about the future introduction of advanced technologies (chemical, combustion) for the processing of industrial waste. By applying combustion technologies the discarded goods are destroyed and the value added to components and materials is lost. This means that their introduction will be justified if the total environmental impact and costs are lower than those made for the collection, transportation and processing of discarded goods by disassembly systems. However, the legislation will require that one processes the discarded goods so that a minimum recovery percentage is obtained (70%). In addition, it is assumed that the future shortages of oil and mineral sources will demand recovery rather than the destruction (burning) of discarded goods. Therefore the application of the combustion option is beyond the scope of this thesis. Considering all aspects included in the design of disassembly systems, the emphasis lies on the economic and technical issues provided that the rules of legislation are fulfilled. The disassembly design approach suggested should be comprehensive and applicable to any type discarded good, now and in the future. It should be related to the available design theory and extended with new recovery issues. Finally, the systematic approach should be applied in practice, in order to show its power and benefits.

In summary, the aim of this research is: ***to develop a comprehensive and systematic procedure to design disassembly systems for recovery of discarded goods. It should be based on economic effects, while the legislation rules, including environmental aspects, are fulfilled. The suggested systematic approach should serve the needs of company managers and designers who are attempting to develop and implement disassembly systems. In addition, some guidelines for the design of sustainable products should be given.***

## 1.7 Structure of the dissertation

The lay out of this thesis is arranged as follows. An extensive literature study is given in Chapter 2. The aim is to review what has already been achieved and what still needs to be done. On the basis of this, it is concluded that the systematic development of disassembly systems is the most important issue that has not been investigated. To achieve satisfactory results the design process should be carried out on the basis of the available knowledge and experience, and extended with new issues.

Chapter 3 briefly concerns the design issues and shows the link between assembly and disassembly. These two processes have many things in common. Therefore, to understand disassembly one should be aware of the essence and structure of assembly. In addition, the integral design of an advanced assembly process and system is described. In this view, the engineering design segments are regarded as a powerful tool while designing assembly (disassembly) systems. It is emphasized that this is possible because of the drastic changes in product design, which facilitates assembly and makes it a feasible process. By contrast, it is concluded that the current disassembly can not be an advanced process since changes in discarded goods are not possible. Nevertheless, with this restriction in mind, the disassembly systems should be as efficient and flexible as possible to compensate the imposed disadvantage.

The determination of the disassembly strategy is the most sophisticated and important step from the entire design of disassembly systems. In Chapter 4, a new method is introduced to define the disassembly strategy. Its applicability is explained and illustrated with a practical case. This chapter describes how to approach and solve disassembly problems.

A complete systematic approach for the design of disassembly systems is described in Chapter 5. It consists of five design phases and a number of steps that should be executed when designing such systems. In addition, the structure of the current disassembly systems are represented along with the necessary tools and associated equipment. Based on this, some assumptions are made concerning the development of advanced disassembly systems in the near future.

Chapter 6 describes the applicability of the suggested systematic approach for the design and implementation of disassembly systems in practice. Various cases are worked out that show the benefit of using this systematic approach. The results were obtained in a close cooperation with industrial firms. The suggested disassembly systems have already been implemented in practice.

In the final chapter, conclusions are drawn about current problems concerning the reuse of products and materials, and how they should be approached. The applicability of the proposed systematic approach is deliberated and justified. It is concluded that more disassembly systems should be implemented, in order to solve the problems associated with reuse of products in due course. In addition, some recommendations for further research are given.

## 1.8 Conclusions

There is no doubt that the development of sustainable production has become a priority of our entire modern society. This issue brings new aspects to the production and reuse of industrial products. The product life cycle is considered as a closed chain and every producer has to contribute in closing this chain in the most efficient and environmentally friendly way. The introduction of the concept "sustainable production" will cause significant changes in the legislation, market, production, consumption and reuse of products. New factories will have to be developed and introduced in practice for the processing of the fast increasing flow of discarded goods. One of the environmentally conscious and efficient ways to solve this problem is disassembling the abandoned goods and their reuse. This requires the development of a comprehensive systematic approach concerning the design of disassembly systems.

In this chapter, the issue of the reuse of discarded goods and materials was discussed. It can be seen that this is a comprehensive topic that comprises a lot of different aspects. To achieve satisfactory results, the efforts of various specialists are required. To make disassembly and reuse an attractive and profitable process, the design of products must be executed from a concurrent engineering viewpoint with regard to the total life cycle. This requires the development of advanced design methods and software tools, which will help the designers to assess a product during the conceptual design phase and to develop sustainable products. For this purpose, the current discarded goods should be analyzed, disassembled, reused to some profitable extent, and disposed of in an environmentally friendly way. Based on the experience obtained from this process, new design methods and technologies should be created. This implies that the most important issue is how to deal with the increasing stream of abandoned products. They can only be reprocessed in a proper way by the design and implementation of disassembly systems. Therefore, an exhaustive literature study should be executed in order to find out what problems have already been investigated in this field and what more needs to be done. While all activities should be considered, the emphasis lies on how to develop advanced disassembly systems related to current and future demands.

# Chapter 2

# Review of literature

## 2.1 Introduction

The item "recovery" has been defined in several different ways depending on who attempted it: economists, industrial engineers, mechanical engineers, public relations divisions, managers, etc. The meaning of recovery differs with the level and branch that is being considered: national, industry, company, plants, departments, or customer level and for what purpose it is being introduced. As was mentioned in Chapter 1, today both customers and some governments demand that manufacturers reduce the quantities of waste generated by their products. Customer pressure is increasing because of the environmental concerns and rising product disposal costs. Facing these problems, many companies and organizations are considering recovery, striving to solve some "hot" issues in this field. The aim is to improve their image and to generate a profit from recovered products in the near future.

In this chapter, some of the recent and current developments in the field of recycling and disassembly are described. It is suggested, that the entire process of reuse of discarded goods and materials is not a single but rather a complex issue. It comprises a lot of different aspects and each of them has its contribution and influence on the final results. In this context, the present chapter describes the developments and applications of disassembly from different viewpoints, and in particular the information available in the literature concerning the topic of this research: the design of disassembly systems. Based on an exhaustive literature review, some conclusions are drawn and recommendations for further research are given.

## 2.2 Disassembly product design and life cycle

In the previous chapter the "pull" and "push" factors concerning the disassembly issues have been discussed. For any one of the reasons mentioned, various companies are facing the recycling dilemma. Considering this issue throughout the entire product life cycle would contribute to:

- Decreasing production expenses.
- "Green" image.
- Saving money value added to materials and products.
- Closing the loop of the product life cycle.

In the last few years, rather drastic changes in the perception of the product life cycle have been seen. This new vision is created as a result of the growing interest towards the reuse of products and protection of the environment. In the ordinary concept, the life cycle of a product is considered up to the point the products are discarded by the customers. The idea to close the life cycle of the products and to reuse them is not new. For instance, material recycling has shown satisfactory results concerning the reduced impact on the environment, lower energy consumption and the recovery of materials during solid waste management. The recycling of paper or plastics, for example, is a long-term workable concept. The reuse of car components, such as second-hand spare parts, is also a well known solution. A hypothesis can be made that the same concept can be applied for all types of products. As was explained, the old interpretation of the product life cycle includes in general the following stages:

- Design.
- Production: material extraction, material processing, manufacturing, assembly.
- Usage.
- Disposal.

To make reuse of products possible this concept is changed and new aspects are involved in more comprehensive models, see Figure 2.1. In this context, the ordinary concept should be extended with the following new aspects:

- Reuse.
- Disassembly.
- Remanufacturing.
- Recycling.

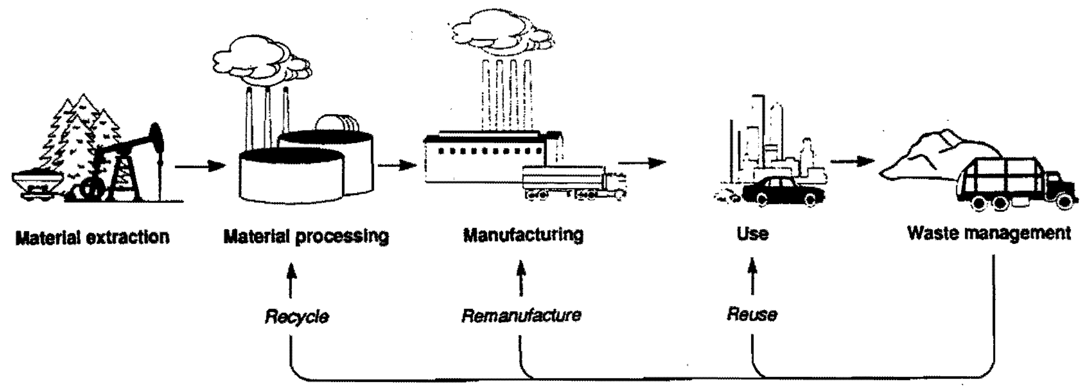



Figure 2.1: Phases of the product life cycle [U.S. Congress, 1992].

The suggested model emphasizes the raw material acquisition through manufacturing, disposal and reuse from scrap. This approach is applicable for material recycling. Concerning the discarded products more issues should be involved. Some of them are represented in the model shown in Figure 2.2. This model includes most of the significant phases that have to be considered through the product design. It implies that in the early design stage most of the meaningful characteristics are set and no changes can be made during the other life cycle stages. This means that design for reuse should be considered in the beginning of the life cycle. In addition, all the consequences for the other stages should be regarded since there may be contradictions between their requirements and constraints. This requires the development of methods that will support the designers while they deliberate and evaluate all the product life cycle's stages simultaneously. The life cycle concept has been recognized as a basis for sustainable industrial production. However, no company has yet introduced an integral method that would fulfil all requirements. But several have applied elements of this approach. Many authors are convinced that while designing for the environment, in the early stage of product life cycle, a certain profit can be generated. Therefore, they believe that the environmental issues will force a change in our design, production, usage, distribution and disposal methods. This should result into a minimized impact on the environment, occupational health and use of resources. Although this concept is widely regarded as the basis for reuse of products and reduction of industrial waste, its current stage of implementation into the early design stage is rather limited. This is because of a lack of information about what exactly should be involved in the new design methods, what the most significant problems are with the current design, and how they can be avoided. It has been concluded that at the present the designer is only left with general advice on how to consider the product life cycle and to try to find a solution that satisfies requirements [Seliger, 1993].

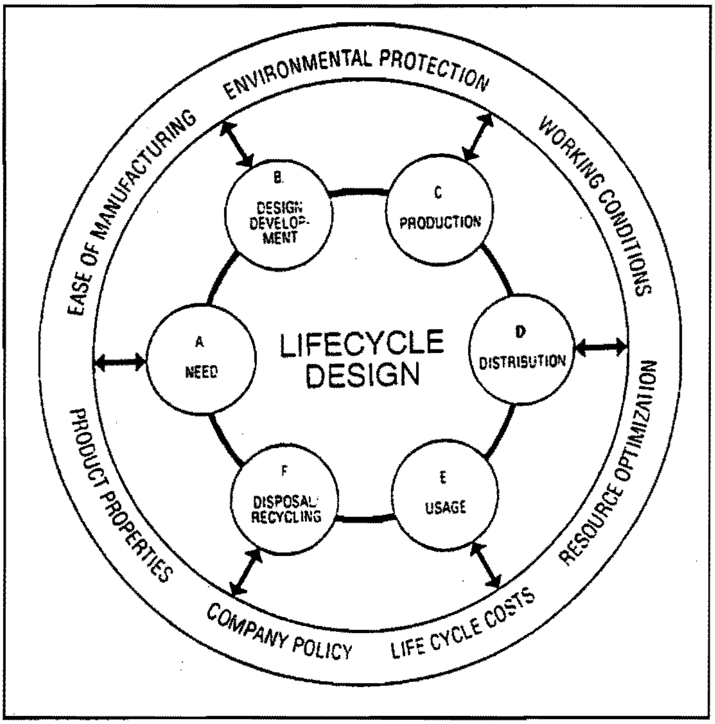



Figure 2.2: Life cycle design concept [Alting, 1993].

In the Netherlands, an attempt has been made to develop a procedure for the design of green products by execution of a project called PROMISE:"Product Development with the Environment as Innovation Strategy". This is a joint project of twelve Dutch organizations, including the Ministry of Economic Affairs (EZ) and the Ministry for the Environment (VROM). The project is devoted to the promotion of the green eco-design in medium-sized companies. The main issue is to make clear, by means of practical cases, that environmental product design is not only beneficial to the environment, but that it also has economic advantages for companies. The current result of this project is the creation of a guide for the design of environmentally friendly products, called:"Manual for Cleaner Product Development" [Brezet, 1995]. It is aimed at designers and managers who are involved in the product development process. The design procedure for environmentally-oriented product design includes seven main phases, which are divided into a number of steps. It starts with the planning and organization of a pilot project and ends with the evaluation and suggestions for further planning, see Figure 2.3. In addition, for the generation of the eco-goals and concepts, a matrix is produced that involves three main phases of the product life cycle: production, usage and disposal. The most important aspects that influence the environment are involved in this matrix: materials, energy and toxicity. This implies the quantity of raw materials included in the product, the necessary energy for its production and the waste and emissions that return to the environment. By using this matrix the designer can approach the eco-design in the beginning of the development process. The results that have been achieved by companies are promising. It has been observed, that often a 30% to 50% reduction of the environmental impact is feasible in the short run.

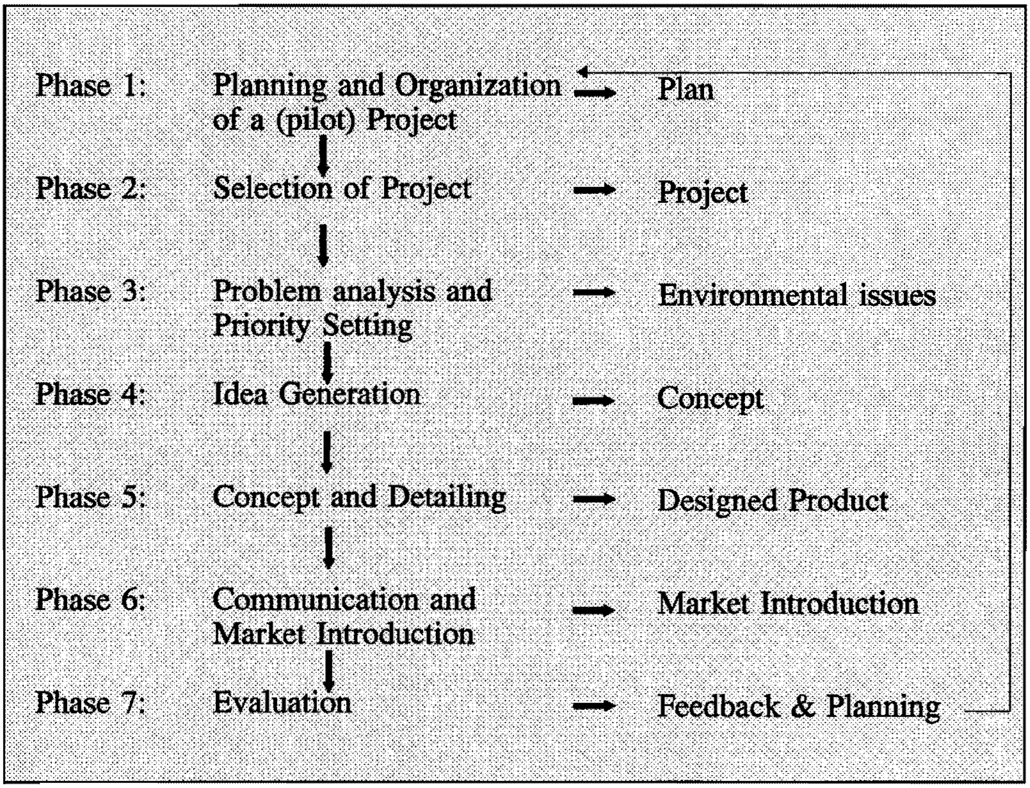


Figure 2.3: Procedure for environmental product design [Brezet, 1995].

Within PROMISE, a second important study was carried out. It contains eight examples of green products [Riele, 1995]. This paper represents the results from various environmentally-oriented product designs in detail. It shows that eco-design can be accomplished without resulting in higher production costs. In general, PROMISE deals with the environmentally friendly development of consumer products. It offers a procedure explaining how a green product design project can be carried out. However, the information is limited to environmentally friendly recycling and the disposal of materials.

It does not consider the design of durable and complex consumer products, where disassembly should also be involved in the beginning of the design process. This means that the suggested procedure can not be used for every purpose related to the design of sustainable products. It should be extended with disassembly issues where adequate design tools for development, disassembling, recycling and reuse of durable and complex products are involved.

As a continuation of PROMISE, further research is being executed [Hemel, 1995]. It aims to support the management and Research & Development activities in companies concerning the integration of environmental demands in the early stage of product development. During the project, a procedure has been developed called "Readiness Assessment for Implementing Life Cycle Design Strategies". In the first stage, this procedure will be introduced in 100 small and medium-sized companies in order to validate the applicability of the suggested method. However, besides the environmental aspects, the other aspects of product life cycle should also be involved in this procedure in order to achieve a complete design method. The future results of the project will show to what extent the suggested procedure can contribute to the development of sustainable products.

## 2.3 Some examples of design for recycling and disassembly

The development of a new life cycle concept and environmental product design has resulted in the introduction of various recyclable products. The designers do not restrict their efforts to material recycling only, but also consider the aspects of disassembly friendly design as a requirement for the reuse of durable and complex consumer products.

Disassembly is regarded as a means for recycling discarded goods. The entire disassembly process consists of various levels that have different implications as was seen in the previous chapter. In this context, DFD (Design for Disassembly) is a step down from DFS (Design for Serviceability) and it is executed in order to replace an item and relocating it for subsequent reassembly (disassembling of parts from copiers - Rank Xerox). Parts may also be forcibly separated by means of dismantling, which results in breakage. When developing DFD, DFA (Design for Assembly) should be the first consideration and starting point. Some of the developments of DFA will be discussed later in this thesis. The application of DFA is considered by many authors as the first step towards successful disassembly. Further, the results obtained from the practical activities are converted into guidelines for disassembly. They contribute to an environmentally responsible design, which entails the capability of reusing products, components and reducing the harmful waste stream. However, not every material used in industrial products can be recycled. The first step when designing "green" products is to use fully recyclable materials only. Product designers and engineers should not only be able to envisage the consequences of their decision in all aspects of the primary life cycle, but also in secondary life cycles. This implies that materials can be reused for another purposes, according to the cascade principle, if they do not satisfy primary objectives anymore.

### 2.3.1 Recycling of household appliances

The first fully recyclable product was produced by a joint venture between GE Plastics, Pittsfield (Massachusetts) and Fitch Richardson Smith, an international design firm based in Columbus [Remicht, 1991]. The product is a completely recyclable kettle. The components are snapped together and fasteners are avoided. The concept involves redesigning a product with many complex components, fastener joints and different materials. The new product requires only standard materials, which can easily be recycled, and a minimum number of fixed joints. In this case the reservoir, base, lid, rear cover, cross clamp and toggle are injection molded with modified oxide. Handle grip and lid grip are molded from thermoplastics elastomer. The parts are joined together by snap-fit connections. Only two screws are used to attach the heating element. All these features of the UKettle will simplify the disassembly and recycling operations. According to the authors, it is important to label parts with a material name and number, which will also facilitate the disassembling operator.

In addition, GE Plastics has developed a conceptual refrigerator-freezer that involves the principles of design for disassembly and illustrates the benefits of 'green' engineering. The concept product consists of a minimum of different materials that are compatible for combined recycling. They can easily be identified by molded-in logos thus facilitating the entire disassembly process. Because of its special features, the new design offers a modular approach to disassembly. The design team claims that by using this concept the refrigerator can simply be pulled apart for recycling [Noller, 1992]. Based on the experiences obtained by developing the products discussed above, GE Plastics has established some design rules for disassembly and recycling, see Table 2.1.

The pilot projects that have been executed by GE Plastics show that the disassembly issues should be considered during the early design stage. Only in this way, satisfactory results can be achieved during the disassembly and recycling stage. The same approach, for the design of disassembly friendly products, can be used by other firms that deal with recycling. More efforts should be spent on the collection of information concerning the current problems associated with disassembly and recycling. The proper design solutions for various disassembly problems can contribute to the establishment of more comprehensive design rules and prevent problems in the new designs.

Table 2.1: GE Plastics' rules [Remich, 1991].

| | |
|---|---|
| * | use compatible materials |
| * | use recyclable materials including bonding aspects |
| * | minimize material count using the least number of different polymers |
| * | design for easy separation, handling and cleaning |
| * | simplify potential uses/sers of products and parts |
| * | use two-way snap fitsbreak points on snap-fits |
| * | provide easy standard identification for all materials |
| * | identify separation of cuts points |
| * | use a molded-in material name in multiple locations to accomodate cut points |
| * | avoid secondary finishing operations such as painting, plainting, coating and so forth |
| * | avoid toxic materials/foams blowing agents (CFC's), heavy metals and so forth |
| * | minimize waste in production |
| * | understand side effects of processes and equipment emissions such as paint vapour and abusive molding |
| * | avoid inserts |

Other researchers are also investigating what kind of joint techniques should be used in order to facilitate the disassembly process. Some of the results found in the literature are in contradiction. In general the recommendations are related to the avoidance of fasteners and screw joints. But Babyak [1991] offers fasteners that will facilitate disassembly. This means that no common and comprehensive rule can be established and every design should be approached differently, according to the particular requirements. The results of various researches concerning the formulation of design for disassembly rules are treated in a German standard [VDI, 1993]. These results should be considered by the designers of new sustainable products. In this way, the designers can extend their knowledge, which would contribute to the development of the most feasible design concepts.

Most of the efforts concerning the recycling of household appliances are devoted to refrigerators and freezers. These products use a chemical gas in their cooling system called chlorofluorocarbon (CFC). In the literature it is known as freon as well. This gas does significant damage to the earth's ozone layer. The environmental problem is enormous and it also concerns the man's health. This is the reason that recycling of refrigerators became a need in many industrialized countries.

In the USA, the Appliances Recycling Information Center is taking back discarded refrigerators and recycling them [ARIC, 1994]. The recycling process includes four main steps:

1) Collection.
2) Processing.
3) Shredding.
4) Sale.

Besides the removal of CFCs, the ferrous fraction is recycled and reused as secondary raw material.

In Germany, a number of recycling factories for refrigerators can be found. One of them is the firm THYSSEN-Sonnenberg, which is engaged with the reuse of discarded refrigerators. The concept involves the reuse of more material fractions than these recycled by ARIC, such as: glass, cables, capacitors and plastics. The main issue remains the processing and neutralizing of the freon. A disadvantage of this activity is that the recycling process is labour intensive. In addition, RWE Entsortung AG, which is located in 15 cities, has also set up disassembly facilities for the recycling of household appliances.

In the Netherlands, there are a few companies occupied with the recycling of refrigerators. As was mentioned in Chapter 1, the amount of discarded refrigerators in this country is huge. The most advanced companies for the recycling of refrigerators, among others, are Coolrec B.V. and AVR Recycling B.V. Their main issue is to neutralize the CFC's. In AVR Recycling B.V this is achieved by burning the freon. The firm claims that in this way 99.965% of all CFC's can be exterminated without damaging the environment [AVR, 1993]. Coolrec B.V. has a completely different approach. It passes the CFC's and the PUR foam to a degassing installation. There the freon is processed and neutralized. The end product does not contain freon and can be reused. According to the company this is the only reliable and environmentally responsible way for freon to be neutralized. Both companies have dismantling lines where the refrigerators are broken down into a number of pieces. These facilities are simple and labour intensive. To generate a certain profit and to be competitive in the future, the companies are striving to optimize their dismantling process and to introduce more mechanized operations. The problem associated with the recycling of refrigerators will be discussed in detail in Chapter 6.

Besides refrigerators, other household appliances are also targeted for disassembly and reuse. Matsushita Electric Ind. Co. is regarded as a pioneer concerning recycling and disassembly in Japan. A washing machine produced by the company can be disassembled with a screw driver alone. Although positive results have been achieved by other firms too, a Hitachi spokesman said: "We have just begun to think about Design for Disassembly" [Hulme, 1993].

### 2.3.2 Recycling of automobiles

Today Germany is the leader in automotive recycling technologies. The severe legislation rules compels companies in this country to take back their products at the end of the life cycle. Cars that are no longer in use are usually passed on by their last owner to one of the many car recycling firms. There the vehicles are broken up in hammer mills (shredders). Then, the ferrous and non-ferrous materials are separated by means of proper techniques. Almost 95% of the ferrous components are recovered for recycling. However, this technology produces the so-called light shredder waste. It contains glass, leather, various plastics, wood, textiles, etc. These material fractions are approximately 20% from the total car's weight. After shredding they are dumped in the landfill. As was mentioned before this will be no longer possible because of the rising disposal costs. This fact and many others require a completely different approach to recycling. Companies must reduce the current waste by selectively disassembling and reusing materials and components as much as possible. Moreover, in the near future the cars should be 100% reusable, which requires design for recycling. This means that the companies should investigate the recyclability of their old products and create rules for the design of fully recyclable cars.

Facing the new requirements, BMW (Munich) has set up a pilot recycling plant in Landshut [Siuru, 1990]. In this factory, the engineers can determine the best techniques to disassemble cars and recover components and raw materials. After the most feasible operations are executed, the entire disassembly process is registered in such a way that the results obtained can be used for the design of the next generation of BMW's automobiles. This research is concentrated on the following issues:

- Recycling of materials from discarded cars.
- Reducing the amount of waste for disposal.
- Reuse of some valuable components from discarded cars.
- Establishing design rules for production of the next modifications.

The BMW's concept for recycling, which is represented in Figure 2.4, shows that some parts are disassembled before the body is sent to the shredder. The aim is to reuse components that still have acceptable quality and to reduce the amount of scrap by recycling such components. The remanufacturing of engines, starter motors and alternators is being considered. Each component is disassembled, tested, remanufactured and reassembled according to strict quality standards. Afterwards the recovered components are sold as spare parts to the market. In addition, during disassembly and recycling some design rules have been developed for the new modifications. BMW's 3-series vehicles have been designed so that more than 80% of the car can be recycled; in the previous modification the percentage was 70%. The company's long-term objective is to reuse more than 90%. This will become possible because:

- The number of materials used in a car are being considerably reduced.

- o Composite elements are being avoided.
- o The number of nonreversible joints are being reduced where it is possible.
- o Parts and materials are marked to allow easy identification during disassembly.
- o Only recyclable plastics are used in the new BMW's generation.

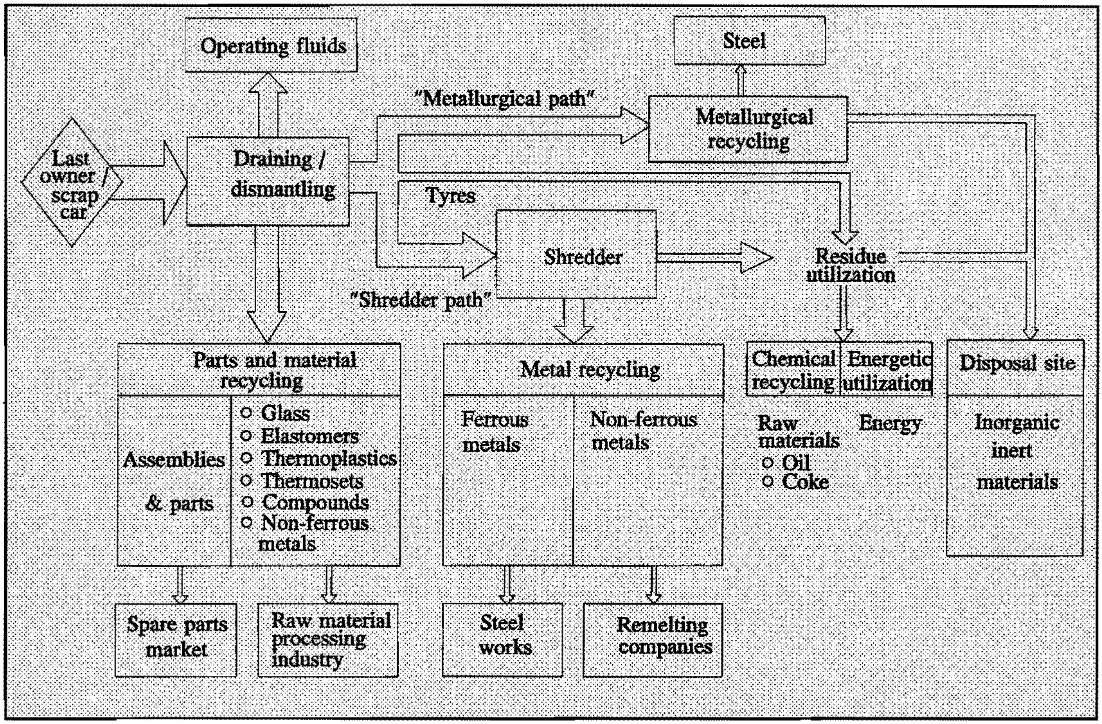


Figure 2.4: BMW's concept for recycling [Wittenberg, 1992].

The BMW Z1, for instance is a car that is also designed for disassembly and recycling. Its doors, bumpers, front, rear and side panels are made from recyclable thermoplastics supplied by GE Plastic. The results from this pilot project are being transferred to BMW of North America, which intends to establish a national network of authorized recycling centers. BMW is convinced that only authorized companies should be designated as institutions that can perform the current recycling of discarded cars.

Volkswagen (Wolsburg) has started a similar recycling project in Leer [Siuru, 1990]. The target of this project is the recycling of a maximum number of materials, which are obtained during the disassembly of discarded cars. First, all fluids like fuel, engine oil, gear oil, dashpot oil, hydraulic oil, break fluid and refrigerant are passed for reprocessing to the mineral-oil and chemical industry. Batteries are also removed and recycled. After these operations are accomplished, the cars are disassembled and recycled in a similar way to BMW. During disassembly, the most suitable destruction techniques have been identified for the various VW's modifications. The aim is to establish a standard disassembly routine for all models. In addition, they examine the requirements for the planning of ergonomic and efficient disassembly processes, and the development of special machines and tools for disassembly. In addition, the establishment of an integrated recycling network with the necessary investment, manpower and existing recycling potential is also being considered. Based on the obtained experience, the definition of principles for design, production and future car reuse have been established.

A number of the current German-built cars already use recycled plastic materials. For example, the new OPEL "Calibra" and "Astra", contain many parts made from recovered plastics of old models. This has been widely achieved through the reuse of the plastic components such as bumpers and seats foams. They are being included in new cars and additional applications are being identified. While designing new cars, OPEL intends to reduce the number of plastics in order to facilitate recycling. The company's goal is to reuse or recycle about 100% of the plastics used in the above-mentioned models by the year 2000.

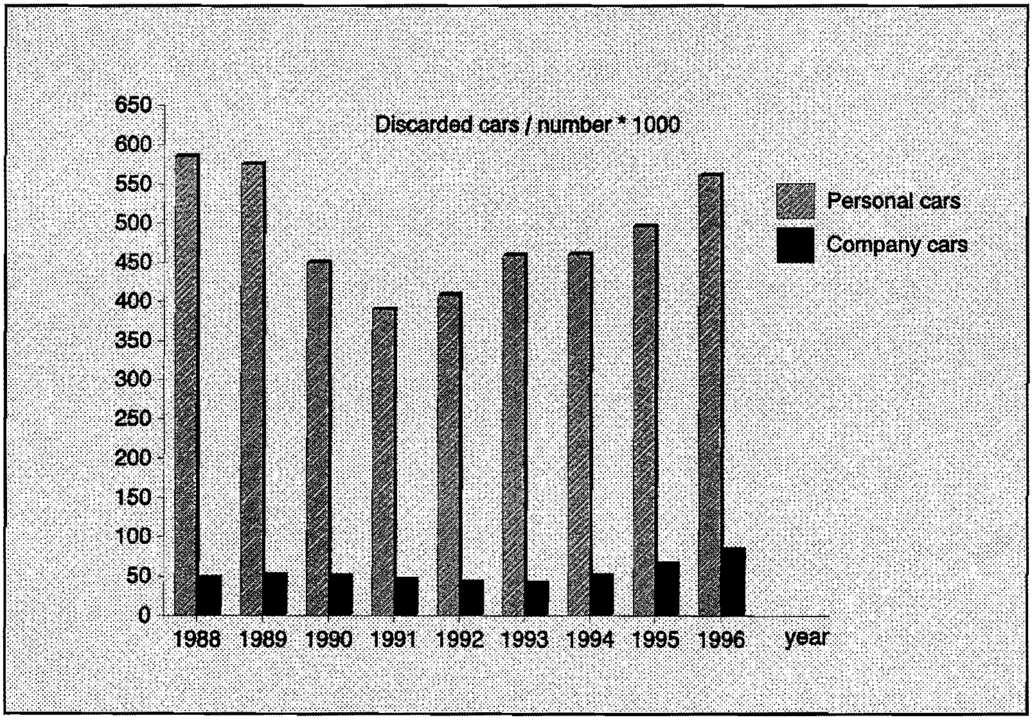



Figure 2.5: Prediction of discared cars in the Netherlands [ARN, 1993].

In the Netherlands, an association known as STIBA was founded in 1985 [Beck, 1993]. The goals of this institution are to consider the best options for a car's recycling in a specific environmental and economic manner. STIBA has estimated the amount of discarded cars that can be expected till 1996, see Figure 2.5. In addition, in 1990, a company to dismantle the models of BMW was established. Besides the generation of a profit, the company's aim is to determine to what extent the cars can be disassembled in the way they have been assembled. Furthermore, the results should give insight into the costs of introducing a disassembly line in practice. The aim is also to reduce shredder waste from 250 kg to 50 kg per vehicle. Similar activities have been carried out in another project, called "Goes". It concerns the recycling of the VOLVO-400 series. It was partly sponsored by the government and it is part of a total implementation plan for the dismantling of discarded cars.

A special association called Auto Recycling Nederland has been established to monitor the recycling of discarded cars [ARN, 1993]. The companies involved in this organization are:

- BOVAG (service firms).
- FOCWA (repair firms).
- RAI (car producers and importers).
- STIBA (car dismantles).
- SVN (shredding firms).

This organization is responsible for the developments in the market, the relation with the recycling centres, the transport of discarded cars, logistic support, information, etc. The aim is that all abandoned cars in the Netherlands will be processed without environmental impact and have a profitable activity.

Japanese companies are also considering the recycling of their products since the legislation in Europe will press them to take care of their discarded goods. Japanese manufacturers are now obliged by law to label the recyclable parts in every product [Hulme, 1993]. Toyota, Nissan, Mazda and Honda are collecting used bumpers for recycling. They are large enough to make their separations and recovery feasible.

Another concept for the recycling of materials is offered by Fiat. They used old materials to provide new ones, which will be introduced in a lower priority part in comparison to the original one. In this way the materials' life cycles can be extended before they are finally dumped in landfill. This concept, called "Recycling Circuit", has already been set in motion for the new models. More than 20 dismantling firms situated in North Italy are involved in this project. First, the fluids and batteries are removed, after which the cars are disassembled and various components and materials are recycled. The bumpers and the other poly-propylene parts are collected and sent back to the Fiat's production facilities after washing and floatation. These secondary products are used for the production of parts with lower quality requirements for the Fiat-Tipo. The glass is also separated and sent to the glass industry for the production of bottles. Fiat recycled approximately 25,000 cars in 1993. Because of the satisfactory results, the intention is to recycle 100% of the discarded cars in Italy.

Automobile companies in the USA are responding to recycling by the execution of extensive activities in the so-called Vehicle Recycling Partnership. This is a consortium founded by Chrysler, Ford and General Motors [Dvorak, 1993]. Their goal consists of two aspects:

- Developing a technology that allows recycling of materials in an economically and environmentally acceptable manner.
- Designing cars for easy disassembly and recycling when they are discarded.

For instance, the Chrysler LH models have complete material descriptions molded into plastic panels, which makes the reuse more efficient.

Other manufacturers including the PSA group (Peugeot-Talbot and Citroen), Renault, and Mercedes-Benz are also engaged in setting up recycling research in various aspects [Cairncross, 1992]. With regard to their initial goals and approach they can be compared on a lower level with the other automobile companies.

Similar issues and trends can be observed when considering the recycling activities in the automobile industries. In general, the manufacturers are trying to recycle as many materials as possible from the discarded cars. For this purpose, some poisonous materials like engine oil, brake fluids and battery acid are removed before shredding. These operations do not increase material value but make the remainder of the materials of the car more acceptable for recycling and waste disposal facilities. In addition, some valuable parts are disassembled, tested, remanufactured and sold as spare parts. When it is economical feasible, some materials or parts are sent to specialized recycling companies for further treatment. During the disassembly of cars, a lot of information is collected and used to develop rules and strategies to design the new models. The described approach, which is used by the automobile companies, can be regarded as a systematic way of solving a problem in the field of disassembly and recycling. It can be used as a basis for the development of a general strategy for the recycling of various discarded goods.

### 2.3.3 Recycling of electronic and electric goods

Like many automobile companies, the electronic industry is also facing the recycling issue. The German government has introduced special rules for the dumping of electronic waste. It has been concluded that the discarded electronic products should be treated as harmful waste. According to the legislation, only after removing the toxicity materials, the products can be disposed of in the landfills. Similar rules have been introduced by the Dutch government which requires special processing of discarded electronic goods. The Tokyo city council has also set demanding procedures for the disposal of TV sets. Present levels of consumption of electronic goods will cause an enormous waste management problem. These devices not only constitute a problem from an environmental viewpoint, but also a source of reusable materials.

Philips, producer of a huge quantity of consumer electronic products, is also thinking about the disassembly and recycling of its goods. One of the firm's departments Mirec, has set up a small experimental dismantling factory for discarded TV sets mostly produced by Philips. This department has more than 40 years experience with waste treatment. The following primary objectives have been achieved:

- Environmental recycling of consumer electronic products.
- Minimizing the amount of waste.
- Maximizing the reuse of materials.

During disassembly the TV sets are broken into the following main fractions: screen (59% of the total weight), housing (22%), circuit board (11%), etc. Before performing recycling, some of the capacitors, batteries and other harmful components are removed. The remaining components and materials are disassembled and sorted. The intention is to see how disassembly can be executed, what are the current problems and in what direction the efforts for designing recyclable products should be concentrated. The result should be the establishment of guidelines for:

- Design for disassembly.
- Design for recycling.
- Design for reuse.

Furthermore, in the Netherlands the development of disassembly facilities for reuse of consumer electronic and electric goods are carried, among others, by the firm Van Gansewinkel B.V. At the moment, a comprehensive market investigation is running along with the establishment of a disassembly strategy. In parallel, the design of a disassembly system has already started. The company is striving to be able to disassemble various types of consumer electronic goods and even to combine them with the recycling of household appliances.

In Germany, last year Siemens A.G. spent about 20 million DM on garbage disposal. This considerable amount of money will be increased even because of the tougher disposal rules in the coming years. This fact will push the company to think about recycling and disassembly and to take urgent measures for the reduction of the waste stream. To do so, Siemens A.G. has invested 50 million DM in recycling in order to reduce 1.5 million tons of scrap from electric and electronic equipment that are produced each year. Because the German government is developing even more demanding rules for disposal, the investments in reuse of discarded products are justified. In this context, Siemens-Nixdorf has started a programme concerned with the recycling of old computers [Beck, 1993]. Since 1989, the discarded products have been collected, disassembled and recycled, in the recycling centre in Paderborn. The strategy of Siemens includes the following main options:

o Reutilization:
  * second reuse for semiprofessionals.
  * third reuse for hobby.

o Recycling:
  * reuse of components.
  * reuse of components parts.
  * recovering of raw materials.

o Disposal.

Used equipment is manually disassembled in the recycling center of Siemens-Nixdorf. All batteries and capacitors containing hazardous substances are properly disposed of in special containers. The remaining materials are separated and sorted out. The obtained pure fractions are sold to different buyers:

* Ferrous are bought by traditional ferrous-treaters.
* Tv tubes are processed by a specialized company that separates the tubes into screen glass and conus glass. The screen glass can be used as a secondary material in the glass industry, while the conus glass is used for lead production.
* Electronic waste like circuit boards are mechanically reduced and separated by third parties.
* Cables are bought by specialized companies.
* Plastics still are a problem with regard to recycling; the aim is to characterize all plastics in the future so that a pure separation is possible and they can be reused.

This work contributes to the creation of knowledge that helps people design new generations of products which will have to be disassembly and eco-friendly. Because of the activities that have been undertaken regarding recyclability, about 79% of the mass of a computer produced five years ago is regained as secondary raw material after disassembly, separation and sorting at present. Before considering disassembly, this amount was only 30%. The firm's goal is to reuse more than 90% of computers as secondary materials by the year 2000. In addition, other specialized recycling companies have been established, which are involved in the processing of discarded electronic goods. Some of them are:

* The company Zerlegezentrum Grevnbroich has different recycling lines to treat different products like refrigerators, recovery of oil from radiators, recycling of tv tubes, battery separation, recycling of asbestos containing apparatus, processing of electronic waste. They cooperate with Trienekens Entsorgung GmbH, which is a subsidiary of RWE Entsorgung AG [Buhler, 1994].

* Zubling Umwelttechnik is the first company to recycle tv tubes in a mechanical way (for Nokia Display Technics). The tv tubes are broken mechanically and reduced; the chemicals are removed by water, while the ferro is removed by means of magnetic belts. The clean glass is used to manufacture new conus glass.

Furthermore, various recycling companies and research institutes from Europe are participating in a project that deals with the recovery of discarded electronic goods on the highest possible level [Brezet, 1995]. The aim is to find a workable solution to prevent the increasing flow of these goods and to develop comprehensive solutions to increase the value gained out of recovery. For this purpose, the projects should give the answer to important recovery issues, like: establishment of a reliable take-back system and logistics, providing the required information, creating a market for the recovered components and materials and improving the current labour-intensive recovery facilities. The project, which is still on a European level, should be applicable worldwide resulting in an international standard for the optimal recovery of discarded electronic goods.

In Japan, the Association for Electric Home Appliances has established a recycling programme for tv sets. Some of the tv sets of Matsushita are designed for easy of disassembly. For this purpose every part is labeled precisely as regards the materials used. This facilitates disassembly by quick identification of the various materials and execution of the corresponding selective disassembly operations [Hulme, 1993].

Besides the electronic consumer products, the amount of discarded electric tools is also enormous. There were about 9.4 millions electric appliances sold in Germany in 1991 and expected to be discarded in the future [Milberg, 1994]. To support companies that are dealing with the recycling of these products, it is necessary to investigate the most feasible disassembly process. The Institute of Machine Tools and Industrial Management of T.U. Munchen has started a project concerning the development of an adequate disassembly strategy and the optimization of the disassembly of products, which will be disposed of in the near future. According to the established strategy, the products are disassembled into seven main fractions:

- Plastics housing.
- Electric motor.
- Fan.
- Gearing and other aluminum and steel parts.
- Cables.
- Electronic parts.
- Batteries.

It was found that the disassembly process is complicated, inefficient and labour intensive. The main reason is the improper product design. At the moment, the disassembly parameters are being recorded so that it will be possible to supply designers with knowledge to optimize new products and make them suitable for reuse. Based on the existing products and using a special analysis procedure, an optimized product has been developed. It shows the benefit of designing for easy disassembly. The total disassembly duration has been reduced by 45% and simultaneously rationalization in assembly has been achieved.

In addition, the design of flexible recycling centres for electronic devices has started in Denmark. All aspects of the recycling process are considered from a life cycle viewpoint, including environmental protection and material recovery [Alting, 1993]. The issue is to convert all harmful materials contained in printed circuit boards (PCB) in pure useful materials and minimum waste. The plant will accept all PCB from manufacturers that will dispose of them in an environmentally friendly way. At the moment, the development of flexible disposal systems is in motion.

### 2.3.4 Recycling of copy machines

Copy machines are considered to be durable products and their recycling and reuse is different from the recycling of household and consumer electronic goods. Copiers contain more valuable elements that can be reused and incorporated in new machines. In this way the total production expenses can be reduced.

Rank Xerox has been involved with the recycling issue for a long time and strives to use components from the old copiers in the new ones. For this reason the designers of the firm are reviewing the structure of sub-assemblies. They redesign them from a recycling and disassembly viewpoint, which results in an improved product shown in Figure 2.6. Although recycling is a policy of the firm and encouraging results have been reported, the managers are of the opinion that they are far away from the desired goal. As they say:" No one is much past the first layer of the onion right now for Design for Recycling". Rank Xerox has already begun to peel away the onion investing $10 million in design and equipment that will allow used cartridges to be remanufactured or recycled. The firm has given guidelines for the design of disassembly friendly products, which are similar to those offered by GE Plastics.

Rank Xerox seeks complete reuse or recycling of business equipment. In the Netherlands, Rank Xerox has started a pilot project for the recycling of its products. In Venray, a distribution centre of the firm is located, which is suitable to collect the old copiers and to reuse them. The trucks that distribute the new products are taking back the old machines and supplying them to the disassembly plant. This action is part of the integrated supply chain for the reuse of copy machines. It involves the following units:

- Operating company.
- Remanufacturing division.
- Repair area.

- o Disposal operations.
- o Logistic center.

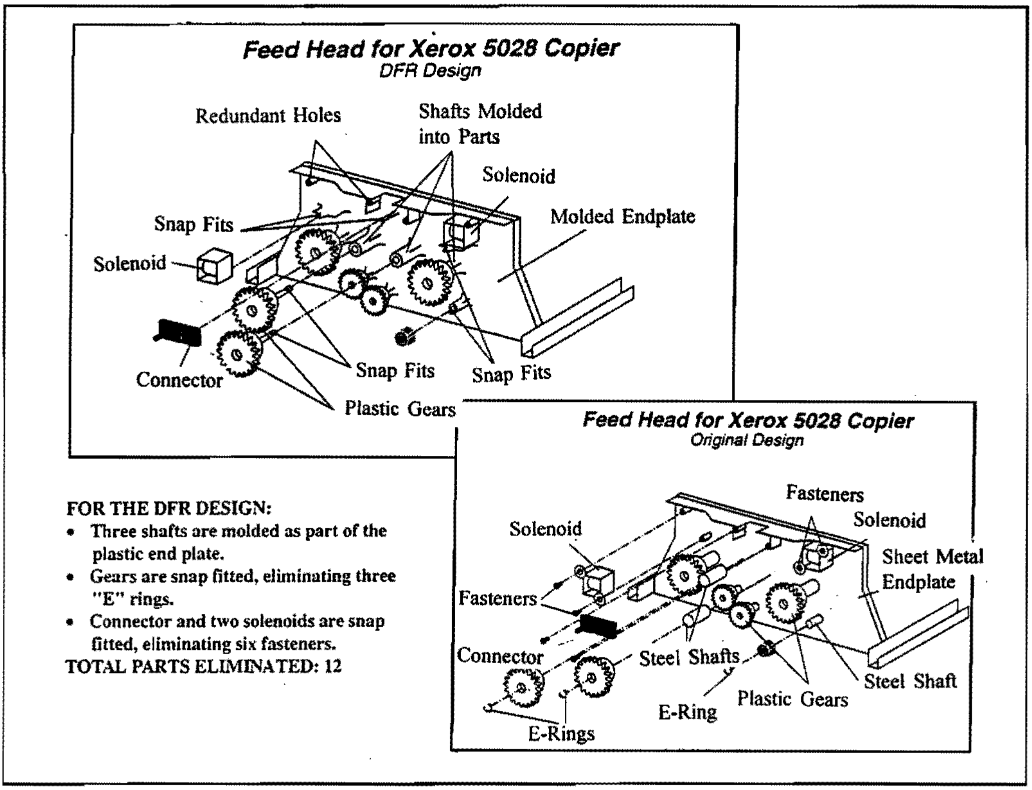



Figure 2.6: Redesign for recycling by Rank Xerox [Remich, 1992].

First, the assets are categorized in four main groups according to their quality and functionality. Then they are disassembled in a number of manual work stations. In every position, the assigned disassembly operations are executed. Then the products are cleaned, inspected, repaired and remanufactured. Remanufacturing involves the disassembly of a machine and replacing worn-out parts, see Figure 2.7. The machines are cleaned and tested to ensure the quality and reliability criteria for newly manufactured products. Some of the most reused components are the aluminum frame and the electrical motors, which have a long life cycle according to the obtained results. After these operations, the copiers are passed to the assembly process and incorporated in new products. Then follows an end test and the recovered machines are supplied to the logistics centre. The company aims to meet the challenge of zero waste material after disassembly and recycling. For this purpose more efforts will be devoted to:

- o Product simplification.

- o Reducing material diversity.
- o Incorporating fully recyclable materials.
- o Development of a consistent disassembly strategy.
- o Development of design disassembly rules.

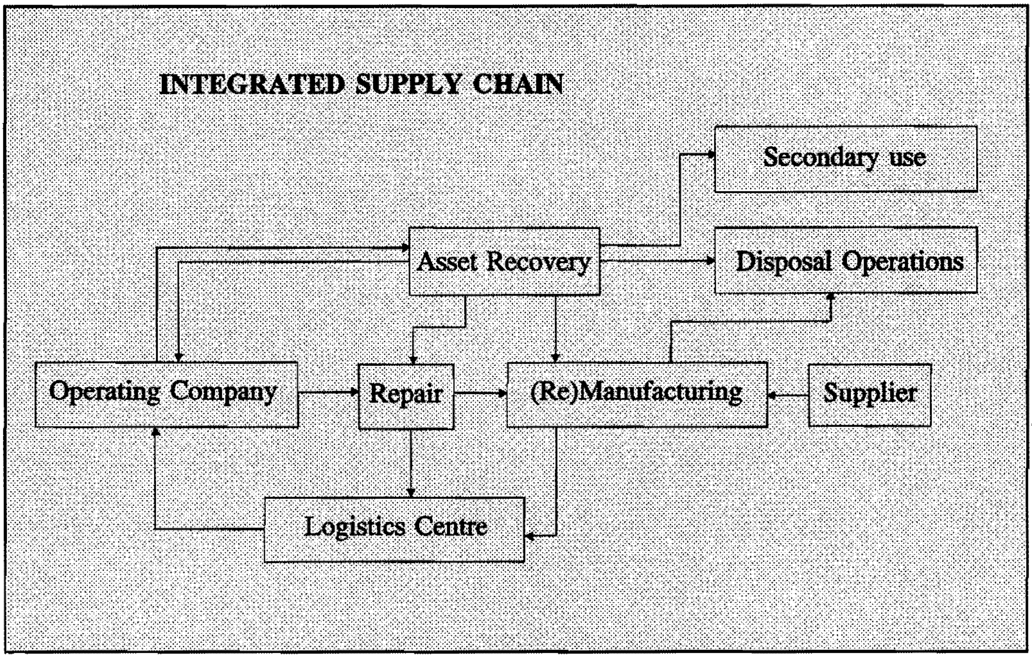



Figure 2.7: Remanufacturing of copiers by Rank Xerox.

In the coming ten years, the efforts of the firm will be concentrated on the design of products that will have the same base structure and only a limited number of components which will be changed in order to introduce new functions and to fulfil future customer demands. In this way, as many components and parts as possible will be reused, which will substantially reduce the production and assembly costs.

Océ Van der Grinten, in Venlo, has also set up a disassembly line for the reuse of copiers, see Figure 2.8. The following main operations are carried out in this factory:

- o Dismantling - removing parts that can not be reused.
- o Washing - the copiers are cleaned up.
- o Disassembly - disassembly of reusable components, their visual control and testing.
- o Ultrasonic cleaning - if possible, parts that are to be reused are cleaned one more time with ultrasonic equipment.
- o Quality control - the recovered parts should fulfil severe requirements; at this stage quality inspection is executed.

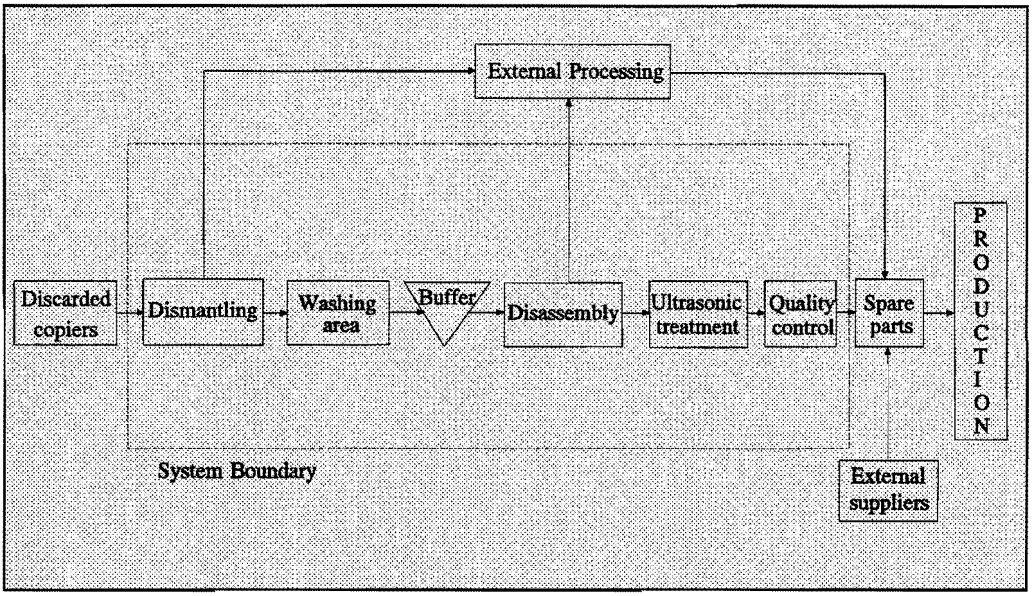



Figure 2.8: Disassembly of copiers by Océ.

After accomplishing these operations, the recovered parts are collected in pallets and stored as spare parts together with the new ones. No distinction is made between recycled and new components since they satisfy the same quality standards. In the near future, it is expected that the return of copiers will increase. This means that the current disassembly facilities will not be able to handle all products. Therefore, the company is considering the optimization of the disassembly process and the development of an advanced disassembly line. However, the recovery of large amounts of copiers will create new problems that have to be taken into account [Sol, 1993]. In this context, if the amount of recovered subassemblies (components) is substantially higher than the number required for the assembly process, this will result in a large end-of-life stock. At the same time, a new product (copier) may be introduced that may have a totally new specification. In this case, the created stock of recovered subassemblies can not be used for the production of the new copiers, which will cause negative financial consequences and make recovery a nonprofitable activity. This requires planning the recovery of goods along with the design of new products and considering all consequences on the company performance, ensuring future positive financial results.

It can be seen that the strategy for the reuse of copiers is different than the one for household appliances, electronic goods or cars. The recycling of materials is not the main issue but rather the reuse of parts and subassemblies, which are used for the production of new copiers. The processing of copy machines starts with removing parts that can not be reused. This operation can be compared with the separation of the poisonous fractions before shredding in the recycling of other types of goods. In other words, the reuse of copiers can be approached in the same way as the recycling of consumer goods while taking some particular issues into account, like financial aspects, logistics and design of new products, which characterize the durable discarded goods.

## 2.4 Disassembly economics and performance measures

There is no doubt that considerations of environmental impact, disassembly and recycling should take place at an early design stage. During the conceptual design, the developer of green products can affect the product design and minimize the usage of raw materials and energy, as well as the disposal of toxic materials. Besides that, the designer should consider the structure of the product and its feasibility for easy disassembly. For these purposes, the designer not only needs advanced design tools but also methods for the evaluation of a product during the conceptual design phase. The evaluation should involve judgements concerning the entire product life cycle; from production of raw materials to recycling and disposal. Because of such considerations, it is very important to introduce suitable performance measurements which can facilitate the evaluation of the product efficiency during its entire life cycle. In this way, the designer would have a tool to make a choice among a number of product concepts and to select the one that satisfies the most economic and environmental requirements.

To access the service efficiency of a product, the concept of Design for Service (DFS) index has been proposed by some researchers [Dewhurst, 1993]. The index can be represented by:

$$I_s = \frac{C_s}{C_s + C_r + (T_d + T_a + T_g).L_l + C_t} \qquad \textbf{(2.1)}$$

where:

| | | | |
|---|---|---|---|
| | $I_s$ | = | design for service index |
| | $C_s$ | = | cost of service items |
| | $C_r$ | = | cost of items that must be replaced by new ones |
| | $T_d$ | = | disassembly time |
| | $T_a$ | = | reassembly time |
| | $T_g$ | = | time of diagnosis or fault verification |
| | $L_l$ | = | appropriate labour rate |
| | $C_t$ | = | cost of use of any special tools or equipment per service task |

The index $I_s$ varies between 0 and 1. A value of 1 represents the ideal case for a service task. Lower ratings are given for replacement of a low-cost part, which requires a lot of efforts and which is labour intensive. It is obvious that long service operations are not justified because this results in a low service efficiency. Furthermore, a measure of recycling efficiency ($I_r$) is offered, as represented by the following equation:

$$I_r = \frac{C_v - C_d - T_d . L_l}{C_{vm}} \qquad (2\text{-}2)$$

where: $C_v$ = value of reclaimed parts
$C_{vm}$ = maximum reclaimed value
$C_d$ = cost of disposal
$T_d$ = disassembly time
$L_l$ = labour rate

These indexes are intended to be used for benchmarking purposes and to establish goals during the early design phase. Using these measures, a software tool has been developed that provides calculation procedures for service and recycling efficiency measures. The software reports estimated disassembly and reassembly times, rates serviceability, and provides the corresponding costs. According to Dewhurst [1993], DFS will be the base for future recycling and disassembly technology. This new method supports the current DFM/DFA developments and the intention is to computerize it further. In this way, the decision process can be facilitated during the conceptual design phase, which would result in the design of disassembly and recycling friendly products.

Another approach to evaluate disassembly is proposed by Navinchandra [1991]. First, he uses a number of performance measures to assess the product design from a disassembly and environmental viewpoint. These measures are called "green indicators". The second step of this approach is to show how design decisions can be influenced by the green indicators. The evaluation procedure is based on a life cycle analysis. The life of the product starts when raw materials are extracted from the environment and finishes when the products are returned and recovered by means of disassembly and recycling. Using these performance measures, the efficiency of the disassembly process can be evaluated and the revenues can be predicted. The following twelve green indicators are proposed:

1. Percentage of reusable materials available in a product.
2. Level of replacement: the ratio between the volume of products that can be removed and the total volume.

3. Time for removing: the time that is necessary to remove a part from the product structure (this time is determined by means of a diagram that gives the expected removable volume as a function of the required time).
4. "Junk" value; this is the total time required for a product to be processed in an environmental way.
5. Separability: the ratio between the volume of separable materials and the total volume. For example, copper and steel can not be melted together in an oven. However, this is possible for steel and aluminum.
6. Life cycle cost: the total costs during the entire product life cycle including those being made for maintenance and storage. This indicator also gives the hidden expenses that are not represented in the production process.
7. Potential recovery: the ratio between reusable and non-reusable materials.
8. Possible recovery: compound and glued materials can be recovered in principle, but in fact they can hardly be separated and therefore are unsuitable for this goal.
9. Serviceable life cycle: the period that a product can be used for the purpose it has was designed for.
10. Duration of usage: the ratio between the useful life cycle of materials and the time necessary for it to be degraded in the environment. For instance, consider a plastic cup that is customarily used for 5 minutes, but it requires many years before it can be decomposed.
11. Total and net emissions.
12. Total amount of poisonous materials in the product.

These measures may be used to analyze the design of a given product, calculate its useful life, determine the expected profit and work out environmental impact. The following approach clarifies how the useful life of a product can be defined. Consider the life cycle of a material that is used for the production of a new product. After usage this material is discarded and may be recycled and reused. Suppose that the total mass of the used material is **m** [kg] and the proportion that is discarded is **Di**. If there are no losses in recycling, all the discarded material should be reused for the production of a new product. This assumption means that the amount of discarded material {**Di.m**} is equal to the amount of recycled material {**Re.m**}. The percentage of the volume virgin material that is necessary for production of new products is **Vi**. Based on these considerations the following equation is valid:

$$Vi = 1 - Re \tag{2-3}$$

where: Vi = percentage of virgin materials
Re = percentage of recycled materials

Let us further assume, that the total time that the customer has used the product is **T**. Then the first period of usage of the materials will be also **T**. Only a proportion **Re** is recycled and used for another period **T**. Hence, the total useful life is represented by:

$$L = T + Re.T + Re^2.T + Re^3.T + .... = \frac{T}{1 - Re} \tag{2-4}$$

where: L = useful life time
T = period of usage of a product
Re = percentage recycled material

This equation implies that if the percentage of recycled materials increases the amount of virgin materials for a new product decreases and the total useful life of the material increases as well. This model can be further extended including secondary markets for recycled products, see Figure 2.9. Let **Di** be the proportion of the total materials that is discarded. Then the proportion that is used in the secondary market is expressed by:

$$Sec = Di - Re \tag{2-5}$$

where: Sec = proportion of materials that is used in the secondary market
Re = proportion of recycled materials in the primary market
Di = proportion of discarded materials.

Assuming no recycled material in the secondary market, the useful life time will be:

$$L = \frac{T_p + Sec.T_s}{1 - Re} \qquad \textbf{(2-6)}$$

where: L = useful life time
$T_p$ = consumer time in a primary market
$T_s$ = consumer time in a secondary market
Sec = proportion of materials in the secondary market.

By using this approach, the useful time of a product can be calculated for the primary and secondary market. In this way, the designer can create a strategy for the extension of the useful life cycle of a product that would also achieve economic and environmental issues.

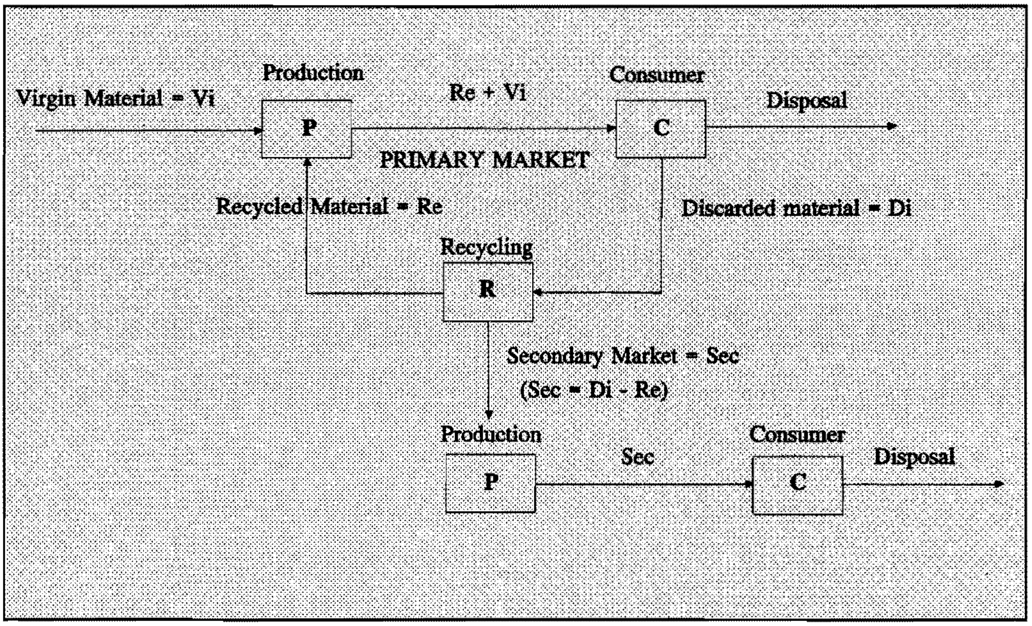



Figure 2.9: Useful life cycle of a product [Navinchandra, 1993].

Other green indicators that should be taken into consideration at the beginning of the design process are the following:

o Replacement strategy: Figure 2.10 gives a method that evaluates the replacement of materials or parts. The vertical axis represents a green indicator and the horizontal one gives the value of the design parameters, which are influenced by the replacement. For example, to reduce the emissions in a car its mass can be decreased by replacing the steel parts by plastics. But in this case when recycling is considered, the total emission will escalate. Hence, the application and choice of plastics should be optimal.

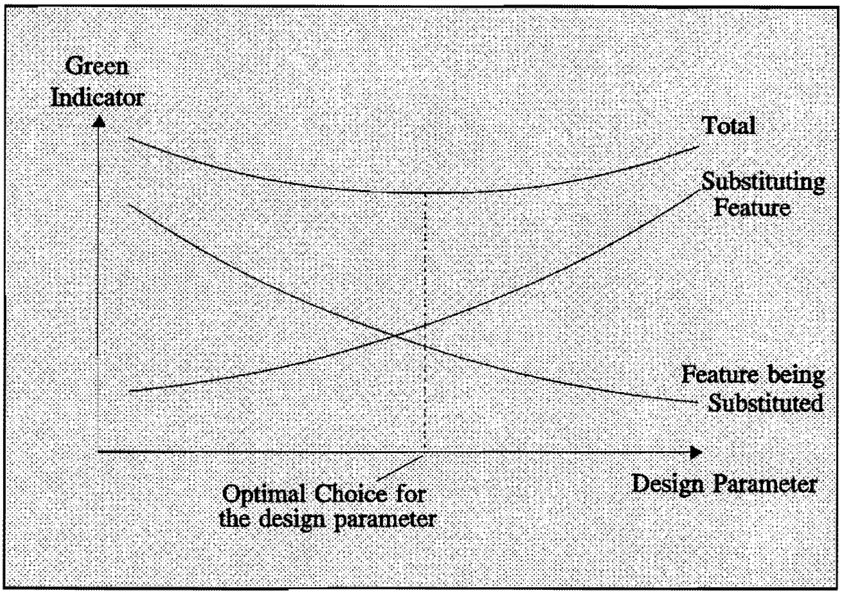



Figure 2.10: Replacement analysis.

- o Design for easy separation: the connection methods should be carefully considered. In general, detachable joints should be used while glue and welding ones should be avoided wherever possible.
- o The choice of materials should also involve the recycling technology. It is very important that the products and materials can be recycled with minimum cost and without emissions.
- o For a proper material choice, a method proposed by Ashby (1993) can be used. In his diagrams different material features are represented, such as elasticity and strength. These charts can be extended with green indicators as given in Figure 2.11. The designer should choose materials that have a lower environmental impact and the same strength. In this way, an optimal selection can be made concerning the project requirements.

In addition, a design tool (ReStar) for environmental recovery analysis was developed to estimate the amount of effort that is put into recycling and disassembly, and the corresponding environmental monetary gains [Navinchandra, 1993]. In the current implementation of ReStar, the disassembly diagram developed by Subramani was adopted. The system has the disassembly time and requirements for disassembling a defined type of discarded goods. During the disassembly it keeps track of costs and revenues for each joint type. According to the developers, this tool can also be used for the planning of the disassembly process.

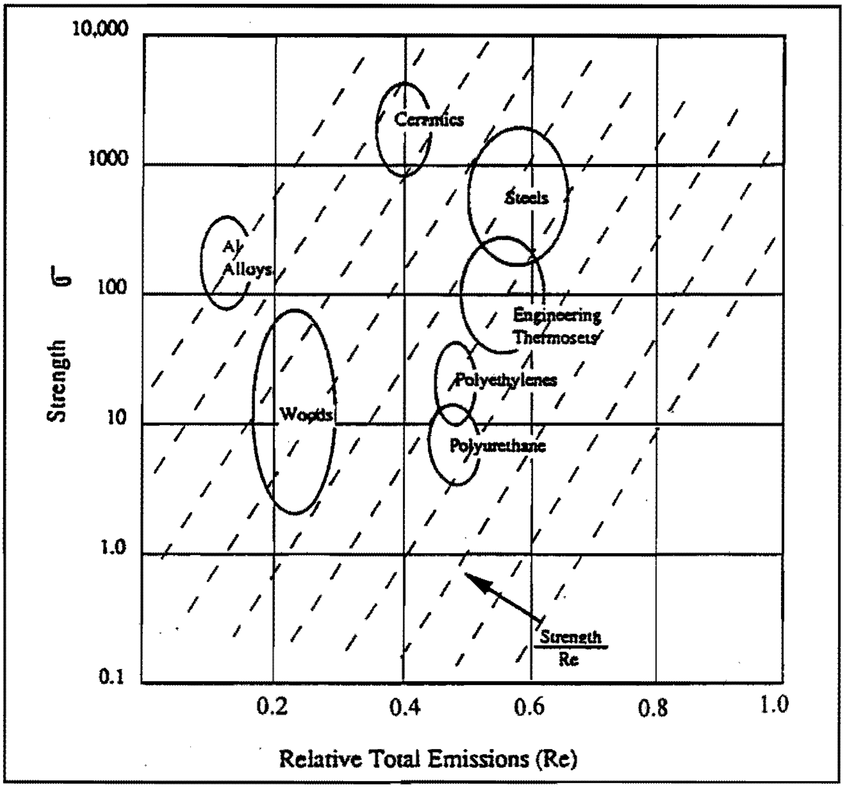



Figure 2.11: A chart for emissions [Ashby, 1993].

And last, but not least, other researchers, organizations and companies can be mention that are facing the issue of reuse of products and materials. Their activities are similar and compatible to those that have already been discussed [Boothroyd, 1992].

## 2.5 Design of disassembly systems

The design of disassembly systems is aimed at developing methodologies for establishing disassembly strategies and configuring the most feasible systems. In order to gain experience and knowledge concerning disassembly, many companies and research laboratories have developed various experimental facilities. As was mentioned before, some European automobile manufacturers (BMW, Opel, Volkswagen, Fiat) have set up dismantling centres. In addition, similar facilities can be observed in other branches for the disassembly of household appliances (Coolrec), consumer electronics (Mirec, Van Gansewinkel, Siemens), copiers (Rank Xerox, Océ) and other discarded goods. During the disassembly process most of the current problems have been identified and solved. This means improving the production facilities 'on line'. In this context, there is no information concerning the systematic design of disassembly systems; this issue has not been considered. In addition, the current disassembly facilities of these firms should be improved, which implies that they badly need a systematic approach to (re)design disassembly systems.

At present, the reprocessing of discarded goods is dominated by manual disassembly and separation of parts. Only some simple operations are mechanized, which makes the disassembly process labour intensive and inefficient. Design of advanced automated disassembly systems is not justified from an economic viewpoint. The reason for the simple disassembly systems available in practice has already been discussed. There is no doubt that the introduction of completely automated disassembly systems is not a realistic issue in the current stage. However, to meet future needs, the possibilities for the introduction of more mechanization and automation in disassembly should be investigated. Moreover, some disassembly operations must be carried out by robots only because of safety and ergonomic requirements. Besides the disassembly facilities developed by industrial firms, various research laboratories and institutions are working on disassembly system design. In Germany, IWF Berlin is developing an experimental disassembly cell for the disassembly of complex electronic products [Seliger, 1993]. It comprises robots, flexible tools and a control system that is able to learn to perform standard operations. The number of operations, disassembly times and tools are determined by using of a planning procedure that consists of four main stages [Hentschel, 1993]. In the first stage, the product is analyzed and valuable components and materials are identified. This provides information for the optimal disassembly level and the number of operations. The following step is the execution of an assembly analysis for the determination of the joint techniques used. This results in the establishment of a strategy for the disassembly techniques required to accomplish the entire process. During the third stage, the possible deviations of the product during usage are investigated. Considerations are made about the consequences for the disassembly process and how it can be facilitated avoiding undesired operations. The approach ends with the determination of the disassembly strategy; usage of non-destructive, partly-destructive or destructive techniques. Based on these results, some disassembly system configurations are developed. The research carried out by IWF Berlin can be considered the first step towards the systematic development of disassembly systems. However, the method does not include information about the environmental issues and the recycling option. More data should be involved concerning the determination of the disassembly strategy on the basis of marketing and legislation requirements. In other words, additional steps should be involved that consider the disassembly issue from a macro level and what consequences it brings to the micro level; this means the design of disassembly systems.

The Fraunhofer Institute for Manufacturing Engineering and Automation (IPA) has started research on flexible disassembly using industrial robots. A pilot disassembly robotic cell for telephones has been designed [Kahmeyer, 1992]. This cell consists of a six degree freedom robot Manutec R3 with a Siemens PCM3 controller. The robot is monitored by an IBM computer used as a cell controller. A special multifunctional pneumatic gripper and a DC-driven screwdriver have been designed and integrated in the cell. The telephone bottom is fixed in a flexible disassembly fixture and the disassembled parts are stored in pallets for transportation. The entire process includes manual and fully automated disassembly operations like:

- Manual supply of products to the cell.
- Manual fixing of the body and cutting of cable connectors.
- Unscrewing of the body and loudspeaker unit.
- Unclamping of snap-fittings of the body.
- Cutting of the cables.
- Disassembling and handling of rigid and non-rigid parts.

The cell is equipped with a sensor for gripping force and opening position. In case of disturbances, the cell controller can switch to another software program with different parameters or can call for an operator. The designers claim that the reliability of the robotic disassembly system is 95% for industrial applications. High returns on investment is expected because the time necessary for the disassembly of a single telephone is less than 3 minutes. However, it should be emphasized that these results are only valid for the selected telephone model. The cell was not evaluated concerning the disassembly of various models and types of products. The integration of a number of cells into a complete automated disassembly line was not considered either. Based on the obtained results, a set of guidelines for DFD with a focus on electric products and devices have been developed. They are generally applicable to both manual and automated disassembly, however with different priorities. Since the results of this pilot disassembly cell are promising, computer disassembly by industrial robots is also being considered. The current research of IPA is concentrated on the development of tools and techniques for automated disassembly of personal computers.

Siemens is developing disassembly robotic systems for tv sets. These systems include a disassembly process controller that supervizes the robot controller. The data are collected by a shape recognition system, which processes the information coming from 3D sensors. The disassembly sequences are stored in the robot control units in the form of program modules. These modules are supplied with the required data by the disassembly process control system. A man-machine interface operates the image recognition system. In addition, the design of proper fixtures for manual and automated disassembly was investigated [Ebach, 1993].

Tokyu Corporation is a private railway company serving the city of Tokio. The firm has started an investigation about the application of industrial robots for maintenance work. Adapting mechatronics technology and computer control, a complete robotic cell has been developed for the disassembling and assembling of brake equipment parts, see Figure 2.12. The robotic cell consists of the following equipment:

- Robot with six axes.
- Two rotary tables.
- Rotating device.
- Stokers of attachments.
- Supporting mechanical equipment.
- Robot controller.
- Main control panel.

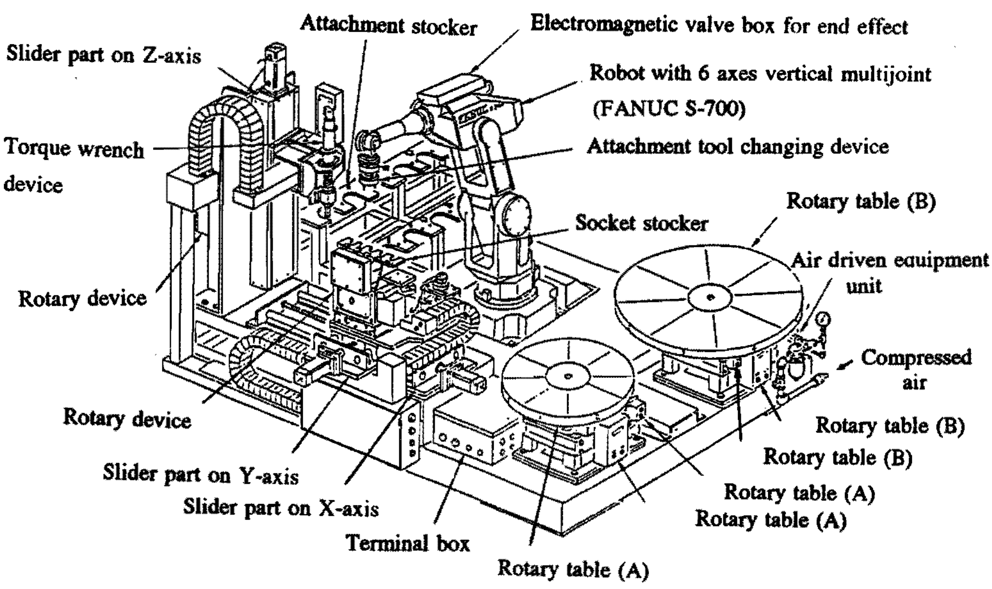



Figure 2.12: Disassembly robotic cell for brake equipment [Miyata, 1992].

The equipment involved in the cell is controlled by software programs stored in a personal computer located in the main control panel. Each of the devices has its own controller, such as a robot controller, slider controller, torque wrench controller and rotating table controller. The information from each controller is transmitted to the main control panel which controls the entire robotic cell. In the case of disassembly, the parts are disassembled on a rotating table (A) and arranged on rotating table (B) where the parts are carried away afterwards. The robotic cell is also able to perform assembly operations. This example shows how assembly and disassembly operations can be executed in the same robotic cell.

The presented disassembly systems with industrial robots are limited to single goods. This is because of the improper product design and wide variety of discarded goods, which make the disassembly process complicated. The results of these projects are important for the recovery of future generation products with advanced disassembly systems including industrial robots. However, the projects mentioned do not provide comprehensive information about the design of disassembly systems at the moment, which should be able to process a wide variety of discarded goods in the most efficient way.

## 2.6 Conclusions

This chapter has reviewed most of the current activities concerning the reuse of industrial goods and the design of disassembly systems. The importance of the problem is recognized by most of the industrially developed countries. The legislation of these countries is the main factor that pushes companies to tackle the recovery issue. However, it is more important to make the process of reuse attractive from an economical viewpoint.

Many researchers and organizations have started investigations concerning the design of green products, development of methods to support disassembly, development of small disassembly facilities, etc. These activities are mainly concerned with the future reuse of goods and materials. The present products available for disassembly and reuse are not considered attractive. The problem that still exists is how to deal with the increasing stream of discarded goods that have high impact on the environment and society, and human health. There is a relatively small number of industrial firms that is facing this problem because the disassembly and reuse of the current discarded goods is a complex process. The generated revenues, after accomplishing the entire process, are rather limited. The experimental disassembly lines, which have already been introduced in practice, are labour intensive. This leads to the conclusion that more efforts should be spent in order to improve the current disassembly facilities and to make the entire recovery process feasible. The first step in this direction is to establish a comprehensive and clear disassembly strategy. It should include a model that contains all aspects influencing this process. The way to execute disassembly, and with what tools and technologies, should be clarified.

This requires the development of a comprehensive systematic approach to (re)design disassembly systems for various products. In this way, the disassembly process will become less complex and more attractive for companies. It will help to reduce their production costs and to improve their facilities. During the execution of disassembly, most of the problems associated with disassembly can be identified and analyzed. The results obtained should help researchers and designers to develop sustainable products that will significantly facilitate their reuse.

In addition, a systematic disassembly approach will prevent the problems of reusing goods of today from being transferred to the future, causing enormous economic and environmental damages. This is the reason that the design and implementation of disassembly systems is the most important issue at the present moment. Referring to the literature, the lack of information concerning the systematic design of disassembly systems is obvious. This is the reason that this research is concentrated on the (re)design of disassembly systems which are able to recover a wide variety of discarded goods, while a profit is generated and the legislation rules are fulfilled. Only the development of industrial disassembly systems and technologies can give a conclusive impulse to the development of easily reusable green products and to the computer-based design of advanced disassembly processes and systems.

# Chapter 3

# The nature of design for assembly and its applicability in disassembly

## 3.1 Introduction

The growing need to decrease the huge flow of discarded goods and to protect the environment are the most obvious reasons for the development of disassembly systems. In spite of all obstacles associated with the recovery of discarded industrial goods, companies have already introduced various disassembly systems. During the system's development phase a lot of problems have been identified, including the lack of a comprehensive systematic approach to (re)designing such systems. In this context, the systematic design of disassembly systems, which are able to process the current and future flow of discarded goods, has been defined as the main objective of this thesis. The aim is to support the current developments of industrial firms engaged with disassembly and to establish a strategy for reuse of complex discrete goods. A systematic design of disassembly systems is a complicated process that comprises different issues from engineering design. It has been formulated as *"a process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of an objective and criteria, synthesis, analysis, construction, testing and evaluation"* [Jones, 1993]. According to this definition, the objective of engineering design is to make use of scientific principles in order to develop systems that are of value to human society and satisfy his needs. Therefore, the first step towards a systematic design of disassembly systems is to have an extensive knowledge of the engineering design. It can be regarded as a science that has internal and external properties, see Figure 3.1. The internal properties are the core of engineering design and represent the fundamental subjects, like mathematics, physics, mechanics, etc. They have not changed much in the last decades. However, the external properties design theory, design methodology, technical systems and special processes and systems, are dynamic processes and they have been continuously developed and improved in the last decades. Regarding the above, one could conclude that the systematic design should be based and related to the external engineering design properties. In this way, the available knowledge and experience can be transferred for accomplishing goals in disassembly. In other words, the designer can utilize procedures that exist already which would considerably facilitate his work.

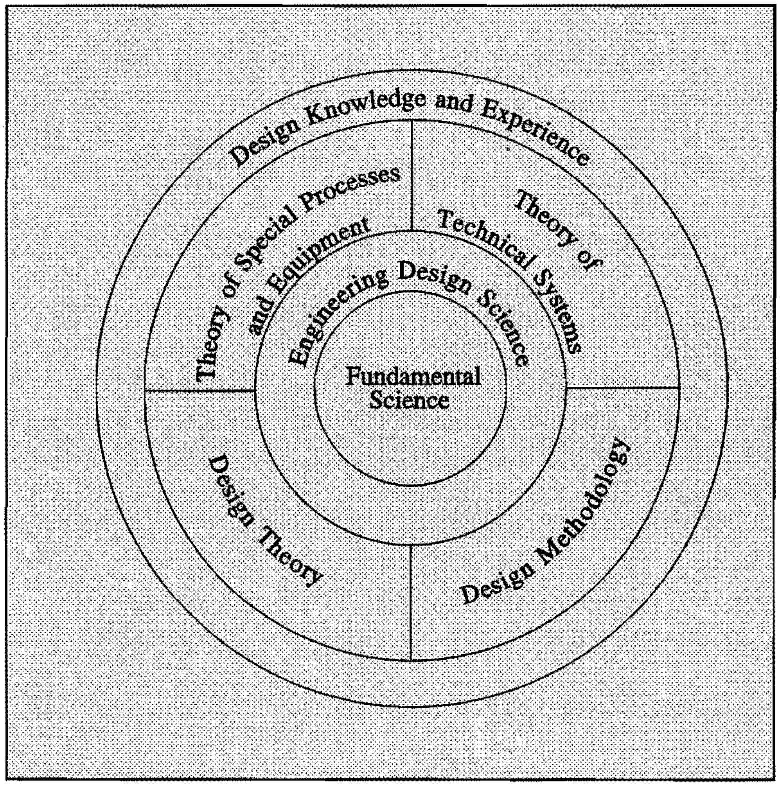



Figure 3.1: Engineering design properties.

This chapter aims to introduce the external engineering design properties as a basis on which to develop a systematic approach to (re)design disassembly systems. The emphasis lies on the issues from engineering design that can be used for disassembly purposes. Besides that, conclusions are drawn about what more should be done in order to cover all disassembly requirements. In addition, the hypothesis is made that assembly and disassembly are closely related processes. Therefore, particular attention will be given to their similarities and differences. The result should be a clear concept concerning the current disassembly problems, how they can be solved nowadays and what needs to be done in order to prevent them in the near future. It is assumed that, in this way, a systematic approach can be created for the (re)design of disassembly systems. It should be used as a reliable procedure by those who attempt to approach and promote the disassembly and recovery of discarded goods.

## 3.2 Design of technical systems

The term "design" is widely used in our society. Since the early 1960s, many authors have developed different design models, which cover the most important topics of engineering design. The aim is to create a procedure that can provide a final successful design, meeting special requirements. The design process has been defined as *"a branch of engineering concerned with the creation of systems, devices, and processes useful to and sought by society"* [Parker, 1994]. This definition is mostly related to the planning and creation of systems and processes (a device or a product are also considered to be technical systems). As any other process, the design process has a complete structure and consists of a number of steps. The design models that have been developed, present the engineering design process as a sequence of activities leading to some results. Two main issues can be distinguished:

- o The structuring of the design process.
- o The carrying out of the design steps.

In every stage of the process, different outcomes are obtained until the desired one is achieved. The point is to find out how the process can be structured and realized in the most effective and efficient way. The answer to this question can be found in different models [Pahl, 1984; VDI, 1990]. They have different structures, number of steps and relationships. However, they establish some fundamental items, which are common for any design model or process. The design process includes many objectives. They are strongly related and have a specific importance that influences the process. To achieve valuable results one should be aware of the structure and the phases of the entire process, and the reason for that ordering. It should be emphasized that design means and requires a step-by-step process. It is like a chain. To facilitate the entire process and to ensure its successful execution, different design methods have been offered and applied in practice [Cross, 1994; Roozenburg, 1991]. One useful design method is the method of the morphological analysis. It offers one an opportunity for systematic investigation and development, and provides the consideration and execution of every meaningful aspect and step. In addition, new advanced methods, such as Design for Assembly (DFA), Design for Manufacturing and Assembly (DFMA), Quality Function Deployment (QFD) and FMEA (Failure Mode and Effects Analysis) have been introduced and have proved their benefits to engineering practice. This means that the external properties of engineering design have been considerably extended over the years. The design methods are meant to support the design process in each stage of his development. The combination and application of proper methods concerning every design phase result in a *design methodology*. It covers all important steps and the corresponding actions that should be taken through the entire design process. A methodology is more open, iterative and flexible than a highly systematized method. The methodology gives a general way to confront problems rather than outlining a rigid procedure. Despite that a little success can be expected from anarchic design activities, a methodology must be identified to accomplish the process and consequently its successful implementation. It is essential that all aspects of realization are considered from the start. This means that the designer should manage the entire process rather than consider separate tasks only, which implies the so-called *"top-down"* design approach [van Bragt, 1992]. A measurement of success is the obvious transparency of the design through the complete transformation process. For this reason, understanding the design structure and the corresponding useful techniques is significantly important.

Besides the design theory, the theory of technical systems is another indispensable ingredient from engineering design. Its aim is to establish a clear idea about the systems nature and the most important items that should be considered during the development process. This approach is based on a comprehensive theory and can be applied to any type system [Hubka, 1988]. Systems theory as a multi-disciplinary science uses special methods and procedures. It combines them into a methodology for the analysis, planning, selection and optimum design of complicated systems. Theoretical concepts are used throughout all stages of development. They help the designer to be creative and to avoid faults due to lack of knowledge, information and experience about the entire item. The theory of technical systems deals with the classification, modelling and development of technical processes and systems. The goal of systems theory is to establish the basis for successful design, criteria for selection and implementation of technical systems. New technical processes and the corresponding technical systems will only be accepted by the market and the community if they show technical and economical advantages, and environmental benefits. The same conditions and requirements are valid for disassembly systems. The question that arises is, how these systems should be designed in order to fulfill the requirements. It is very important in what way the available information concerning the life cycle of products, processes and systems will be processed. The usage life of products is becoming increasingly short. This requires an acceleration of the period for the development of the corresponding technical systems. Moreover, they should be extremely flexible in order to satisfy the growing demands of the customers. In this context, the environmental issue can not be omitted. Even if we suppose that the product life can be extended, for instance by correct maintenance and production of high quality product, the customer still can limit it by his requirements. The ideal situation is a technical system that can carry out all actions associated with production, assembly, maintenance, disassembly and recycling. This issue requires the development of an integral approach for the design of products, processes and systems. Because every step in the life cycle is important, various disciplines should be collected together in order to execute this process. Moreover, they should be applied simultaneously, taking all aspects into account. One can see, that the successful execution of the entire development is one of the most important goals. The design process should be executed adequately, efficiently and quickly in accordance with the market and requirements of society. Each step of this process should be performed with the help of a suitable method, which would facilitate the process and provide final desirable results. In the theory of technical systems, several models and their arrangement have been described. Together with the design methodology another design model can be created, which clarifies how to proceed with the design of technical systems.

Besides the theory of technical systems and designs, other disciplines are also involved in engineering design. For the completion of the design model, special knowledge is required concerning the particular processes and systems. The aim of this research is to establish the items and guidelines for the successful development of disassembly systems. Since these are relatively new issues and there is no relevant information about their nature, the link with other similar processes should be found first. In this way, the basis for disassembly can be established. The goal is to transfer as much knowledge and experience as possible from other disciplines, which can strongly support the entire development of disassembly and recycling. In this context, assembly is considered the basis for disassembly as the correspondence between these two processes is apparent. Although they are different in some aspects, they have a lot of important features in common. The comprehensive knowledge available in assembly should be used for the design of disassembly systems. Moreover, the experience obtained in the past can help and prevent a lot of problems associated with disassembly. This is the reason that the designer should be aware of the developments in the field of assembly and their application in the practice when dealing with disassembly.

## 3.3 Disassembly versus assembly

In this section, disassembly is regarded as a physical process and not as an organizational issue. As was defined before, the aim of the disassembly process is to *"dismount discarded goods (or products) into constituent parts by means of various operations where the obtained parts are not broken and/or damaged"*. A lower level of the disassembly process is dismantling, which aims *"to take apart into constituent and* *destroyed elements by demolishing the discarded goods elements"*. From this point of view, two disassembly techniques can be distinguished:

- o Non-destructive (disassembly).
- o Destructive (dismantling).

Disassembly covers various phases of the product life cycle. During usage, disassembly is applied to repair and maintain products. After the goods are rejected by the customers, disassembly is applied to recycle the materials in the most efficient way. In this context, it aims to close the life cycle chain and to prolong the useful life of goods and materials. Many goods are not repaired due to high costs, because they are not designed for easy disassembly. In other words, the designers and producers have limited their effort to develop products for easy manufacture and assembly. Most of the attention has been devoted to easy assembly since it determines 70% of the total production costs. Moreover, assembly has a large impact on the costs of maintenance and recycling during the useful life and reuse of goods, which is achieved by disassembly. These two processes are segments of the product life cycle and they are mutually related. Generally, they should be considered simultaneously during the early design in order to ensure satisfactory results during all life cycle phases. However, if we consider the current generation of discarded goods, it should be clear that assembly and disassembly have not been taken together during the design process. Therefore, the only goal at this moment can be the analysis of assembly and the determination of its consequences to disassembly. Advanced engineering implies concurrent design of a product, process and the corresponding technical system [Nevins, 1989; Rampersad, 1994]. This is the case in assembly where the design process is carried out according to the concept of concurrent design. Therefore, it should be possible to find out how the developments in assembly can be used to facilitate the systematic design of disassembly systems. The search process should involve three issues: discarded good (product), process and system, which represent the disassembly and assembly variables.

When we design disassembly systems, the starting point should be the analysis of the input flow (discarded goods). This is different in comparison to the general design of technical systems, where the starting point is the (re)design of a product. As was mentioned before, the discarded goods contain compounded materials and various components that have been joined together by means of different assembly techniques. The discarded goods have a fixed structure that has been created during manufacture and assembly. This fact makes the disassembly process very complicated since the input flow (discarded goods) can not be changed. On the contrary, the input can be consciously chosen during assembly so that the process is simplified. This is achieved during the design phase as the product is (re)designed for easy of assembly. It is emphasized that the product design has the greatest influence upon the development of the corresponding process and system. It plays a significant role in the automation of the assembly, product's life and product's quality. If the structure of a product is not easy to assemble, assembling facilities must be more sophisticated, hence expensive, the failure rate of assembly stations becomes higher and the performance of the assembly system will be low. It can be concluded that the particular nature of the input flow is the most obvious difference of disassembly in comparison to assembly. This is the reason why the level of development of these processes differs so much. In order to decrease the influence of this difference, it is necessary to collect comprehensive information about what joints have been used during assembly. For this purpose, the assembly techniques should be analyzed and specified as to what the most efficient corresponding disassembly operation is. Although some assembly techniques can facilitate disassembly, there are many that cause severe obstacles. For instance, adhesive or click joints may be justified from an assembly viewpoint, but they are completely inappropriate for disassembly. This means that in many cases, significant contradictions between assembly and disassembly appear, which should be resolved and avoided in the new designs.

Secondly, the disassembly process can be described in the same manner as assembly by using verbal blocks or symbolic language. In this way, the designer will have a clear picture about the minimum required operations. Moreover, the disassembly variables (product, process and system) are the same as those for assembly. In other words, while designing disassembly systems these variables should be considered simultaneously. However, the discarded goods are not analyzed for redesign purposes but for the determination of a disassembly strategy. For this purpose, the product assortment, structure and components should be carefully examined. They will define the process and system necessary to disassemble discarded goods. This means that the same variables should be considered but they have to be interpreted differently because of the specific input flow. In this context, the number of operations is based on the input flow. A disassembly strategy implies the generation of the disassembly plans and carrying out the optimum plan in the most efficient way. For this purpose, some methods for the generation of assembly sequences may contribute to the determination of the disassembly sequences. This topic is significant for the purpose of this research and will be discussed in a separate chapter.

Thirdly, the design of disassembly systems has been defined as a complicated process. The designers are left to deal with discarded goods that have not been designed for easy disassembly. As a result, the current disassembly facilities are complicated and require highly skilled workers. This is not economically feasible for the firms dealing with disassembly. Although there are severe obstacles, the current disassembly activities should be improved. In this view, the experience in assembly can be utilized in the following way. Before 1980, there were no advanced assembly design methods. Since the development and introduction of the first assembly line for automobiles by Ford in the 1900s, a lot of improvements have been observed. The labour intensive processes were replaced by advanced assembly processes including mechanized tools and machines. This continuous improvement led to the development of advanced mechanized and automated assembly systems. In other words, the designers were able to improve the systems without changing the product design. The design process was carried out according to the principle *"throw it over the wall"*, which implies bad communications between the departments involved in the design and production processes. Despite this disadvantage, the evolution of assembly systems did not stop. The analogy between the early years of assembly and the current state of disassembly is obvious. In fact, today the designers of disassembly systems have to solve similar problems as were met earlier in assembly due to improper product design. In this context, the experience from assembly can be used to solve some problems concerning the design of advanced disassembly processes and systems. For instance, the arrangement of any disassembly station or line can be based on the assembly line configurations. According to the production rate, investment policy and required flexibility, it can be decided which lay-out fulfills the required disassembly system the most. The equipment available in assembly can also be used for disassembly. For instance, various transport systems fulfill the same needs for the supply and transport of materials, components and products. In addition, assembly tools such as screw drivers, pick and place units, and other mechanized equipment can be used with little alteration to facilitate the current disassembly process.

Keeping in mind that disassembly is not the reverse of assembly, new specific problems should be solved while making use of the available applicable knowledge and experience. The specific disassembly issues should be clarified and solved during disassembly of current discarded products. These issues will be considered in the following chapters, while the application of assembly for disassembly issues will be clarified in the following sections.

## 3.4 The assembly process

### 3.4.1 Introduction

The term *'assembly'* is used in different ways in the literature. Usually it is conceived of as something separate from the total production process. In this thesis, it implies the fitting together or joining of separate components or parts into sub-assemblies, and after that into complete products. However, assembly should not be confused with a single joint method. The concept comprises the entire assembly process including the required equipment for its execution, and methods that have successfully been used in this field. As with any other process, assembly has main and secondary functions. Its main function is to join materials, components and sub-assemblies into a complete product. In fact assembly is the last stage of the production process, which mainly consists of the following steps:

1) Production of raw materials.
2) Production of finished materials and components.
3) Accomplishing of sub-assemblies.
4) Final assembly.

The conventional production begins with the processing of raw materials. By means of primary processes (extrusion, casting, pressing, forming, etc.) the virgin materials are transformed into semi-finished materials and parts. After application of secondary processes (cutting, milling, drilling, turning, surfacing) the semi-finished materials and products are converted into a number of single components with a determined structure. In some cases, the production process ends at this point, with the manufacturing of separate products. However, the final principal part of the entire process is the joining of materials and components. This requires the application of an assembly process. The entire assembly process consists of a number of sub-processes that are compulsory if the main issue is to be accomplished. Between the main and sub-functions we find determined relationships that result in a complete structure. The understanding of these items is vital to the entire assembly process. The main function of assembly can be divided into a number of basic functions (see also Figure 3.2 (a)):

- Supplying.
- Handling.
- Composing/Joining.
- Inspection.
- Special processes.

Different authors [Browne, 1985; Andreasen 1988] have suggested a similar division of the assembly's main function. However, it is a difficult task to determine what exactly the number of sub-functions is, since the variety of products requires application of additional special processes or their cancelling. The sub-functions depicted in Figure 3.2 (a) can be considered common to assembly. On the other hand, they can be divided into a number of sub-functions. For instance *supplying* involves storage, separation, grading, positioning and orientation. In addition, *handling* includes allocating, transporting grasping, alignment and insertion. It should be emphasized that the suggested functions do not completely represent an assembly process. It is an integrated and complex operation that involves other processes, which are also performed between the main assembly stages. The function of *supplying* is to move the single components and materials into the assembly working sector. Sometimes this step includes orientation. The function of *handling* is to put the components into a required position and to prepare them for composing. After the last one is accomplished, the transportation to the next work position follows. The purpose of

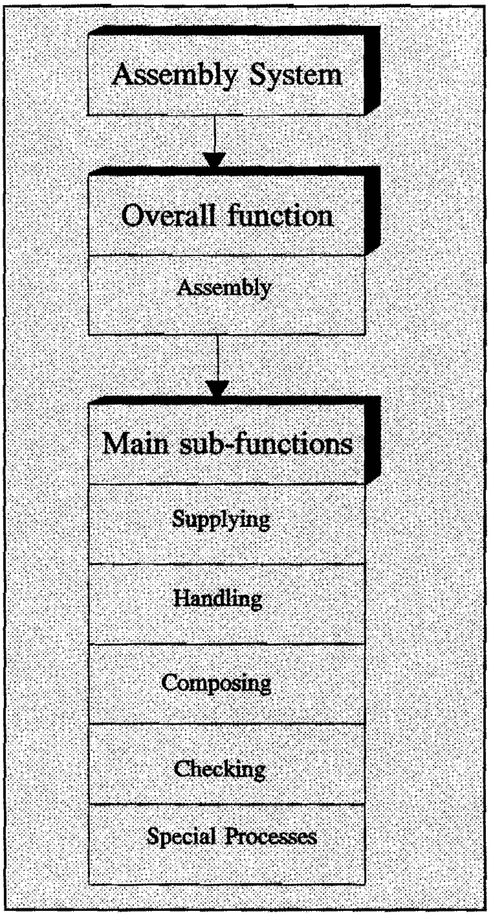



Figure 3.2 (a): Main sub-functions of an assembly system.

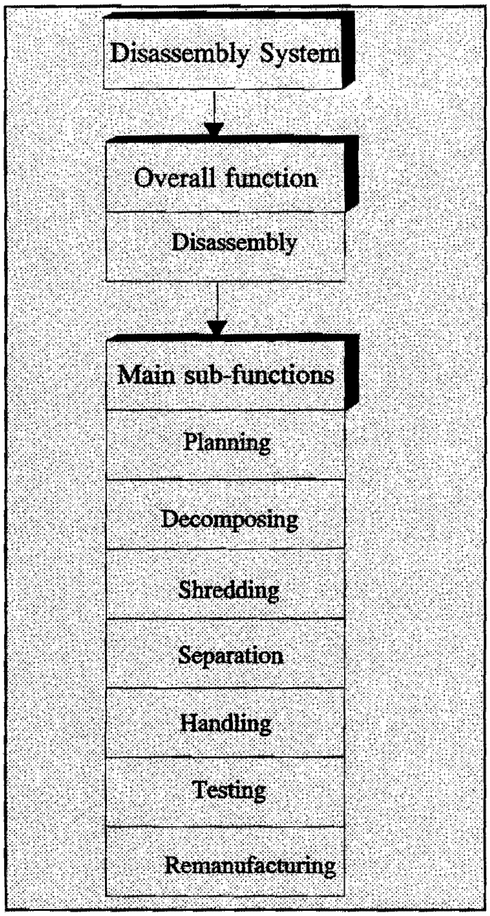



Figure 3.2 (b): Main sub-functions of a disassembly system.

*composing* is to join materials and components. It provides the permanent connection between the components. Composition can be achieved by means of joining, filling, interference, change of form, means of materials, etc. [Andreasen, 1988]. *Checking (inspection)* is introduced in many stages in the assembly process. Its function is to detect whether a particular operation has been carried out as required. The function of *special processes* is to complement the assembly process, if it is necessary. For instance, cleaning and packaging can be considered and applied as special processes. This category may also involve disassembly in order to accomplish some control operations during the production process if required.

The disassembly process can be represented by a similar number of subfunctions, see Figure 3.2 (b). For instance, composing should be substituted by decomposing to achieve the purpose of disassembly. This involves special new functions necessary to accomplish the entire disassembly process in the most feasible way. In this context, a disassembly system should include a shredding and separation function. In addition, in some cases a remanufacturing function is required as well. The essence of these sub-functions will be described later in detail. The other sub-functions can be considered in the same way. This means that solutions for handling, supplying and inspection can be used to develop disassembly processes. For instance, variable transport systems and belt conveyors, used in assembly, can be introduced for handling and supplying operations in disassembly systems. However, the designer should be flexible when using the available equipment for disassembly purposes. In this context, special solutions are required concerning the particular disassembly problems that have to be solved.

As can be seen, assembly is a very puzzling process. Its degree of complexity expands with an increasing number of components and sub-assemblies. For a clear presentation of assembly it is necessary to model the process and to make it more transparent, see Figure 3.3. Process modelling can be achieved by:

- o Pictorial modules.
- o Verbal blocks.
- o Symbolic language.

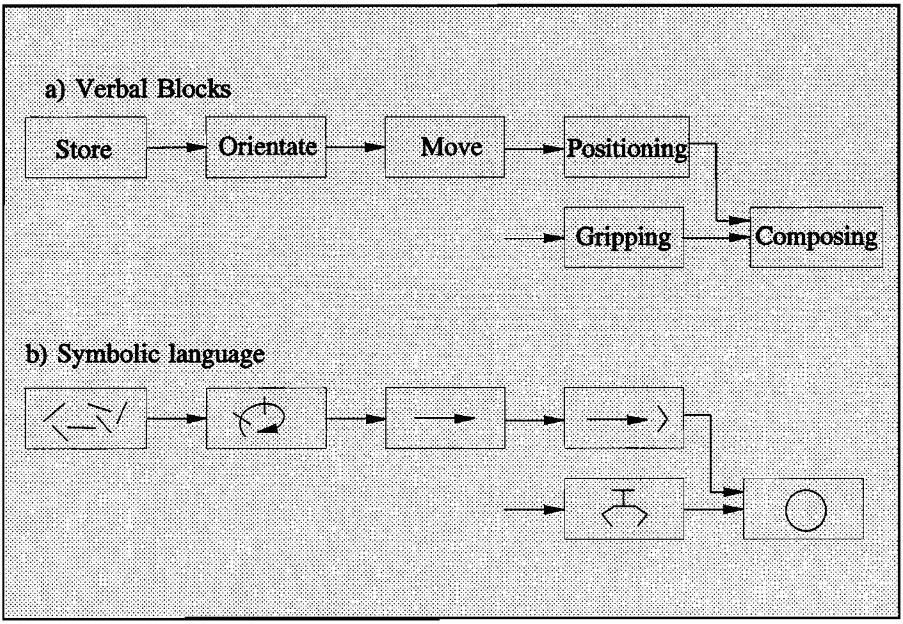



Figure 3.3: Illustration of assembly modelling.

The first method takes a lot of time and is not always clear. Therefore it has not been widely used. More applicable is the presentation of assembly by verbal blocks [Andreasen, 1988] and by means of special symbols, or so-called symbolic language [VDI, 1990]. The method to be used depends on the personal perception concerning their convenience and benefit. As long as a clear process structure is established any model can be introduced. However, for the successful execution of the entire process, many additional aspects should be taken into consideration. As with every process, assembly has different properties and depends upon many variables, which are mutually related. Their nature and influence on assembly will be highlighted in the following section.

### 3.4.2 Assembly variables

Assembly's main function has been determined as a process that joins materials and components for the final production of complete products. To perform assembly and to satisfy the requirements, various technical means have to be selected. They strongly depend on the product structure, since it has a big influence on the entire assembly process. This means that the product design is a very important issue. Different researchers claim that the design phase mainly determines the success in assembly [Boothroyd, 1992; Dewhurst, 1993]. In addition, product design defines the restraints about what type of equipment can be introduced. The integral consideration of a product, process and system development plays a considerable role when designing assembly systems, see Figure 3.4.

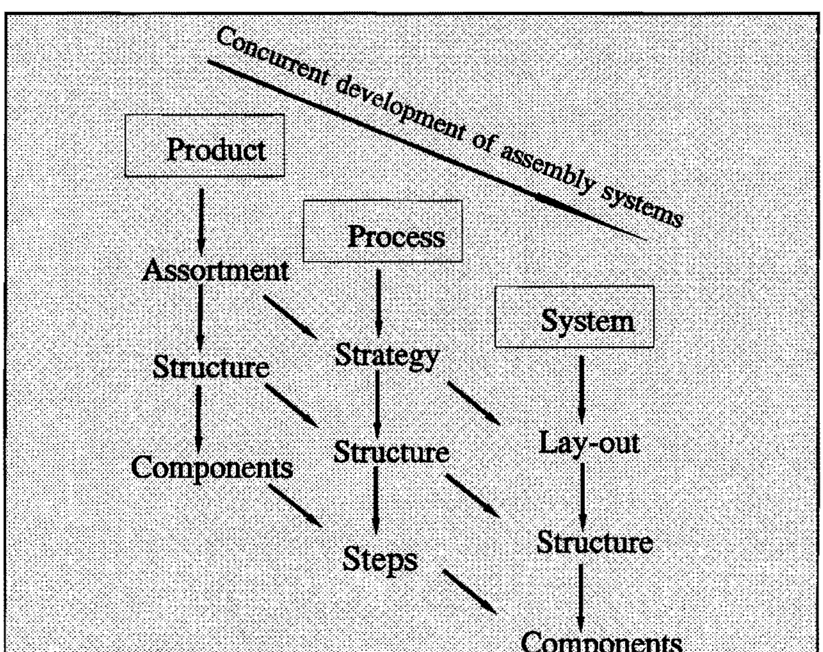


Figure 3.4: Links between the assembly variables.

The **product** can be determined by its assortment, structure and components. The influencing factors related to the these product elements are given as follow:

a) *Product assortment* - technical development, designer skills.

b) *Product structure* - assembly equipment, production process.

c) *Components* - assembly process, operators.

The **assembly process** is influenced by:

a) *Assembly strategy*: it defines how the assembly process should be executed concerning the limitation being made in the design phase. It also determines the level of automation and mechanization, which is based on economical factors, policy of the firm, annual production rate, etc.

b) *Assembly structure*: this factor involves the sequence of the assembly operations. It shows the mutual relations between the operations that bring about the completion of the entire product.

c) *Assembly steps*: according to the product structure a number of compulsory processes should be established. Besides the basic assembly sub-processes special ones can be introduced.

The factors that influence the **assembly system** can be related with the general theory of technical systems. In this case the following items are important:

a) *System lay-out*: the lay-out is determined by the final concept concerning the location of technical means suitable for the execution of the assembly process. The relationships between the technical means are also given.

b) *System structure*: between the system components there are certain relationships. They have a distinct influence on the entire assembly structure.

c) *System components*: they are selected in order to fulfill the required assembly functions. The number and type of components are strongly related to the corresponding assembly steps.

These factors, which usually influence the assembly process, are mutually related. Their concurrent consideration in the design stage is a very important issue for the design of assembly systems as well as disassembly systems.

Being aware of the theory of technical systems, it is logical to consider their common relations. For instance, the link between the product, process and system can be viewed in the following way. A number of product's components and sub-assemblies determines the types and sequence of the assembly operations. The **product structure** also has the greatest impact on the quality and stability of the process. A good design would offer the opportunity for assembly with minimum operations. Another important aspect is the determination of the basic components, after which all auxiliary components are joined preferably in a vertical direction. On the other hand, the required assembly process determines the type and number of technical means and their relations. Similar considerations enter into the relationships between the product components, assembly operation and system components, and between product assortment, assembly strategy and system lay-out.

This discussion clarifies the fact that there are determined relationships between the elements of a product, process and system, which are mutually dependent and influence each other. While designing disassembly systems, the same variables should be considered, taking into account the different nature of the input flow. It would impose restrictions concerning the design of advanced disassembly systems.

### 3.4.3 Methods of design for assembly

Due to the increasing competition, companies are being compelled to investigate the production and assembly costs. The aim is to decrease the expenses for producing a product and to increase the total productivity, which is the goal of every company. It has been found that assembly is a very expensive part of the entire production process. As was mentioned, about 70% of the production costs are related to assembly. This fact pushes enterprises to develop and use rationalization techniques that can systematically improve the assembly process. The general tendency is to introduce more automated assembly systems, because of the rising cost of labour. As a result, the total productivity has to be increased. The key to rationalization of the assembly process can not be found in the production or assembly area, but rather in the beginning of the design process. In addition, possible improvements of the manual assembly and its automation can be achieved after particular design modifications. Therefore, the developer of assembly systems should consider the proper design features in the early design stages as regarding manufacture and assembly of the components. Moreover, during design the restrictions are set about the type of assembly system that can be introduced in practice. These facts clarify why the product design should be considered as a starting point for price reduction and the implementation of the most feasible assembly system.

The assembly costs are related to the design of a product and the corresponding assembly system. The lowest assembly expenses are determined by the product, which should be favorably designed so that it can be economically assembled by the most appropriate assembly system. For the evaluation of a product from an assembly viewpoint and its possible redesign, different methods have been developed and introduced in practice. A common feature of these methods is that they help achieve an appropriate composition in the early stage of the design process. Another benefit is that they promote ideas for part reduction and elimination of unnecessary assembly operations. As a result, the total cost for the manufacturing and assembling of a product are reduced. These methods are based on empirical information and practical experience. In general, a designer should answer a number of questions and then a choice should be made on how to proceed further. The aim is to find out the most effective and least costly assembly method. The most utilized methods in practice will be highlighted.

The *ABC analysis method* is based on seven important questions, see Figure 3.5. They are considered a tool that forces and facilitates the co-operation between product designers and process engineers. ABC analysis has been extended for assembly applications. The key question is: *"What is the total cost of a component or sub-assembly, from its initiations right through to the time when it reaches its functional state after completion of assembly?"* [Lotter, 1984]. This question includes seven fundamental interrogations that are interdependent. They cover all actions related to the assembly process. The aim is to reduce cost and facilitate assembly in every stage of the entire process. The ABC analysis method can be extended with environmental and disassembly issues. It should involve information about the disassembly costs, quality of the obtained components and materials, handling characteristics, etc. In this way, the ABC check list can be used as a tool for disassembly analysis. In the future, the considerations with respect to assembly and disassembly should be combined in a single ABC analysis chart.

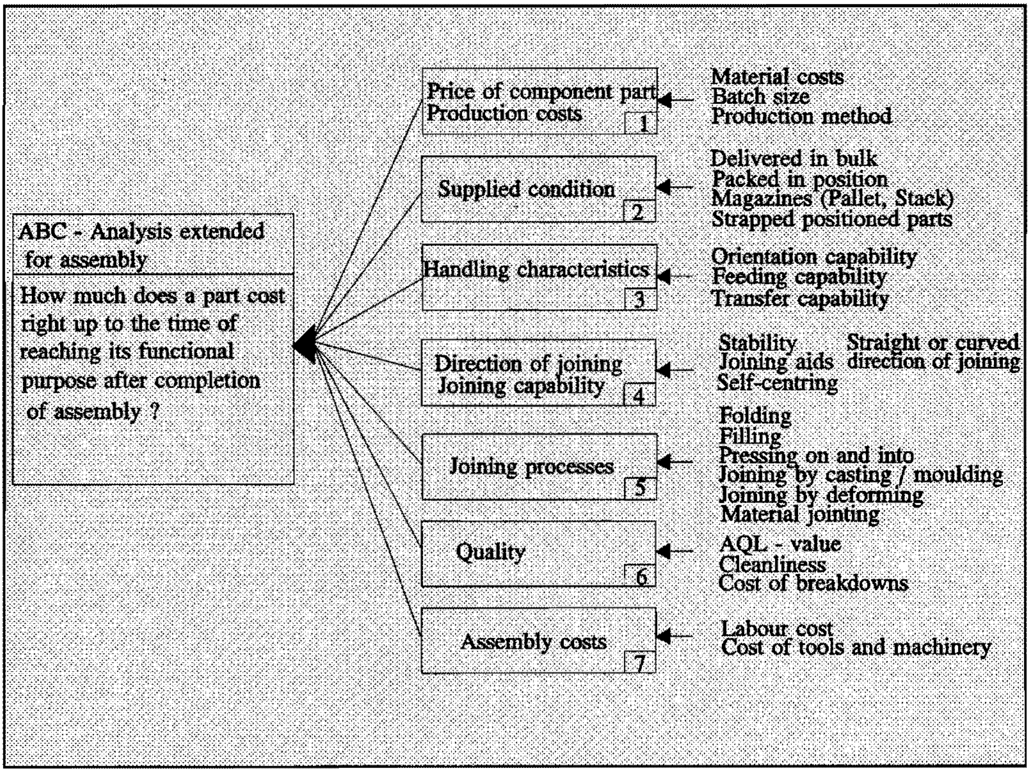



Figure 3.5: The ABC analysis method [Lotter, 1984].

The *Hitachi's method (Assembly Evaluational Method)* deals with the analysis and evaluation of the assembly operations required for a particular product design. For every design the suitability for assembly is evaluated and a suggestion is made as to which part should be removed. This involves the cost for execution of insertion and fitting operations, but no information is provided for components feeding and orientation. Because of this lack of information, design for automatic assembly is not covered [Osashi, 1983].

In the approach suggested by Zorowsky [1987], the assembly functions are considered the most important items to determine the efficiency of assembly. He developed an analysis tool, called *Product Design Merit (PDM)*, to promote redesign and changes in the assembly process, which should lead to ease of assembly. It is based on the assumption that the assembly functions are fundamental in the assembly of any product. In this the handling operations are taken into account, such as feeding, inserting and fastening. It helps the designer to compare his product with other design and assembly operations. The quantitative measures are criteria that determine the best design. However, this method does not provide information on how to redesign a product nor which the most efficient assembly operations are.

In comparison to AEM, the method of *Lucas* has the advantage that it distinguishes manual and automated assembly. The functional analysis is related to every component and results in a conclusion as to whether a part should exist or can be removed. In addition, it evaluates the handling operations for manual assembly and the feeding operations for machine assembly. Analysis of the fitting operations is included as well. The measures for evaluating the efficiency of the process are used as criteria with regard to assembly. In addition, the method assigns penalty factors that are compared to the previous design. In this way, a product can be evaluated from an assembly viewpoint. Besides these positive features, the method has the disadvantage that it does not provide any information about which type of automated assembling system should be developed. The last three methods may have limited applications in disassembly as they only tackle separate problems. Besides that, they can be considered as part of the most popular and widely used method in practice, known as Design for Assembly (DFA).

The *DFA procedure* comprises all advantages of the aforementioned methods. It starts with analyzing the product structure followed by estimating the assembly time and cost. Many companies like Motorola, IBM, Xerox, etc., which have used this method, have reported a considerable reduction of their production costs. The DFA methodology is a systematic approach that comprises all actions which lead to price reduction. It consists of a number of steps depicted in Figure 3.6. In the first stage, the most appropriate assembly system is selected. The goal is to determine which assembly mode and system should be introduced, for instance:

a) Manual assembly.
b) Special purpose machines (high-speed automated).

c) Programmable machines (robots).

This selection depends upon many expected parameters, like the number of parts in a complete product, product assortment, possible investment for reducing the number of operators, number of components whose design should be changed, the total number of components necessary for product variety, number of shifts, the expected annual production volume, pay-back period, capital investment, etc. Using these parameters the most cost effective assembly system is chosen from a chart ("Choice of Assembly Method"). The next step is to analyze the product and to find out whether it is suitable for assembly. This includes improvement of the design to minimize the assembly costs. For this purpose the analysis process involves the development of a process diagram. It shows the number of assembly and special operations required to assemble a product. In such diagrams one can see where the most problems occur associated with the execution of special and complex operations, variety of component, feeding problems, etc. The analysis of the process diagram makes clear where the efforts should be concentrated for the improvement and redesign of the product. According to the DFA method, the first means of improving design for assembly is to reduce the number of components and assembly operations. There are three fundamental questions that determine this step [Boothroyd, 1984]:

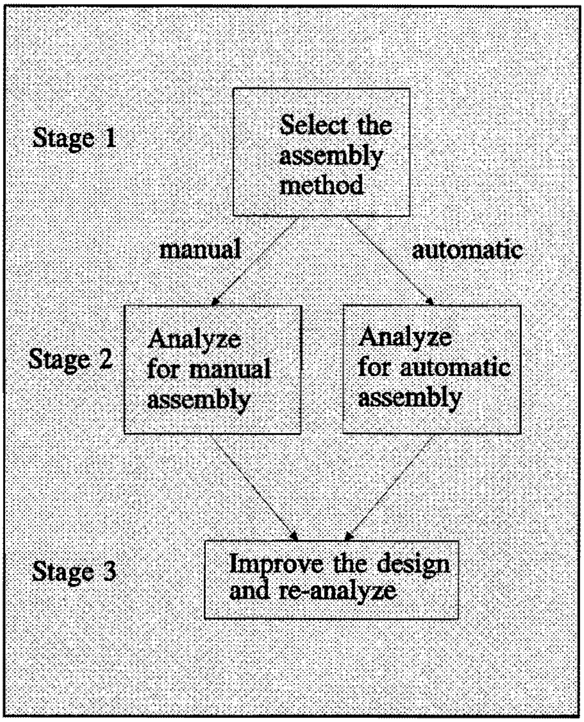



Figure 3.6: Steps in design for assembly [Boothroyd, 1984].

1) Does the part move relative to all other parts already assembled?
2) Is the part made from different material to those already assembled?
3) Is the part separated to allow assembling or disassembling of parts already assembled?

These questions are answered and recorded in a work sheet, where the expected problem points in the assembly process can be discovered. The analysis is then completed and the improvement of the design can begin. The reduction of parts is executed in accordance with the answers to the fundamental questions. If the answer is positive for any of these fundamental reasons, a part can not be removed since it will have a negative impact on the final product properties. In the opposite case, the part will be an object for elimination. In this stage, relevant information should be collected concerning the manual and automated assembly. It includes an estimation of the manual operations and the cost for extra operations. With this information the total expected cost can be estimated during the design stage.

If the results obtained from the analysis are not satisfactory, the *redesign* of a product follows. This process should end with a product that is completely suitable for the chosen assembly method. The reader will understand that a similar approach concerning disassembly is not possible at the moment. The designer can not redesign the discarded goods. This explains why the current disassembly facilities are incompatible to the advanced assembly systems.

The DFA method systematically supports the process of design for assembly. It is very useful for designers who want to learn how to execute the entire process successfully and to avoid severe faults. However, as any other design method, DFA can not be a substitute for the creativity during the (re)design stage. The benefit of this method has been proven in practice. Its combination with other methods can result in a significant reduction of production and assembly costs. It should be regarded as an indispensable segment of concurrent engineering and has to be applied whenever possible. For future design applications, DFA should include disassembly issues. In this way, a powerful tool can be created, which would support the design process and aid the development of advanced disassembly systems.

Besides the technical and economical aspects, the socio-organizational factors are significant and should be taken into consideration when designing technical systems. One of the basic issues for achieving satisfactory results is to motivate employees. People are regarded as the most essential strategic resource of a company. Greater involvement of employees in the development process is of essential importance. This means that organizations and systems should be designed and built-up in such a way that all employees are participating at some reasonable level in the development process. It should be realized that an approach in which the human being is considered as an observer in the production process is not workable anymore. This would result in low motivation which means that it would become impossible to obtain improvements in quality and productivity initiated by employees. With respect to this important issue, a method created by **IPA** can be used to involve the socio-organizational aspects in the development process [Sanders, 1995]. This method takes into account the expectations of the operators during the design and selection of the most feasible technical (assembly) system. In order to determine which the most important system's performance is, according to the operators, a number of criteria are listed in a matrix. By comparing these criteria with each other, a weight factor can be obtained that shows what the most important systems's performance is for the employees and what they expect from the introduction of the developed technical system. The selection criteria, like possibility for communication, improved ergonomics, own responsibility, etc., are determined by the employees. The results obtained from the matrix should be considered to select the most feasible system, while the economical and technical requirements are fulfilled. This method also treats other aspects of the design of technical (assembly) systems, like grouping of similar work stations suitable for automation, mechanization or manual assembly. In this way, the efficiency of the assembly areas can be considerable improved resulting in the development of the most feasible assembly system. The described method should be used together with the DFA method to involve every significant aspect for the development of assembly systems in the early design phase. The applicability of this method will be clarified during the development of disassembly systems in the following chapters of this thesis.

### 3.4.4 Assembly systems

The development and establishment of an assembly system is strongly related to a determined product and the corresponding process. The starting point for the creation of advanced assembly systems should be the product design process. An assembly system comprises a lot of sub-systems as mentioned earlier. The division of the number of sub-systems depends upon the particular cases. For instance, if the assembly process does not have special requirements, the handling system can perform and accomplish the entire assembly process. It should be realized that the number of sub-systems corresponds to the number of required assembly sub-functions.

The main function of an assembly system is to execute all activities required to accomplish the final assembly. If this is necessary, the system has to be able to transport the sub-assemblies to the next position to perform the following scheduled operation. Every sub-function of an assembly system is performed by the corresponding proper equipment. The arrangement of any assembly system can be represented by a three-dimensional grid with respect to the complexity and degree of mechanization (see Figure 3.7).

The most simple assembly system is a single manual work station. The process is carried out by an operator who has simple equipment at his disposal. This station can be supplied with additional equipment, such as component boxes, mechanized tools, indexing tables. Different degrees of semi-mechanized work stations are represented along the X axis. It ends with a fully automated work position where the operator is substituted by a robot. A number of single work stations can be linked to transport systems and integrated into assembly lines with different degrees of automation (Y axis). This integration of linked work stations with a high level of mechanization leads to the development of a flexible automated assembly line. This is a system that can assemble a variety of products. To manage these sophisticated processes, the information stream should be controlled by different types of control systems (Z axis). The highest level in this hierarchy is represented by computer integrated systems.

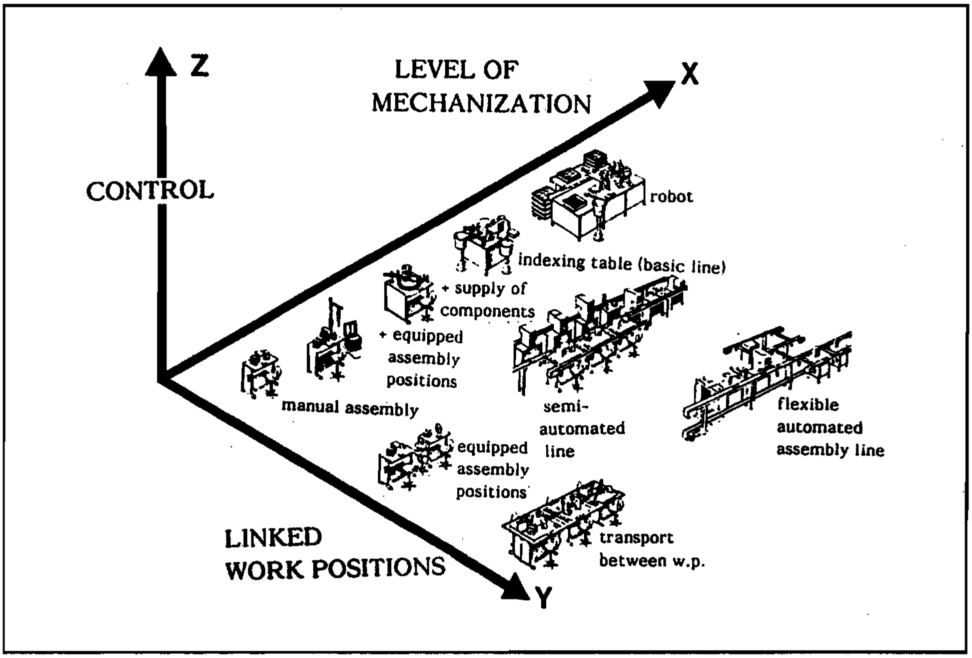



Figure 3.7: Assembly systems configurations [Sanders, 1990].

The arrangement of the assembly positions discussed can vary [Sanders, 1995]. In this way a number of lay-outs is created. The following configurations are possible:

- o Fixed position.
- o Product or line lay-out (sequential).
- o Process or functional lay-out (parallel).
- o Group lay-out (mixed).
- o Cell lay-out.
- o Star lay-out.
- o Matrix lay-out.

The first three lay-outs are considered classical. The others can be regarded as combinations of the classical lay-outs.

The transport system that links a number of work stations can be operated in different ways. According to this feature, various types of transport systems can be distinguished: single positional, synchronized, flexible, with continuous actions, combined. The choice which type of assembly system should be selected depends upon a number of factors and constraints. Most of them are related to the available technology and equipment, economical aspects, required flexibility, etc. After these items have been considered, it is followed by the establishment of the sub-systems and their link to provide the flow of materials, energy and information. In addition, the type of equipment and its arrangement into a more complex structure should be related to the flexibility issue. This means that a system should be able to assembly a variety of products without significant changes in the hardware.

The evolution of the assembly systems took many years and involved knowledge and practical experience from different fields of engineering design. The change in design strategy and production technology has offered new opportunities for the introduction of advanced assembly processes and systems. In the same way, new solutions have to be found to design disassembly systems. At the moment, the general assembly configurations can be used to arrange disassembly facilities. Besides that many tools used in assembly can be applied for disassembly, as was already mentioned. In this way, the development and implementation of disassembly systems can be accomplished.

## 3.5 Application: assembly of rollers for belt conveyors

The following case depicts the utilization and benefit of the application of a DFA method. It is applied to the development of a technical system to assemble the rollers of belt conveyors. The rollers maintain a belt on which different objects can be transported. In practice the belt conveyors are used as individual devices or as a part of complicated transport systems. By linking a number of separated conveyor units, a modern convey system can be developed for the transportation of a number of goods. For instance, in the mine industry coal can be transported over a long distance up to 200 km. It has been proved in practice that this transport system is compatible with automobile and rail transport. The utilization of a conveyor system can be only profitable if the rollers are reliable and have a long life cycle. On-line replacement is an important issue, as well the reuse and recycling of the rollers. These requirements have pushed a company to make drastic changes in its production facilities and organization, in order to satisfy the demands and to be competitive in the international market. The increasing annual production rate required expansion of the production capacity. For these reasons a completely new approach had to be made concerning the manner of production and assembly. The automation of the assembly plant to some profitable extent had become inevitable. Two main requirements were established, which had to be fulfilled by:

1) Production of high quality and reliable rollers.
2) Assembly of the rollers with the most feasible system.

The first requirement is predominantly concerned with the bearing unit since it determines the rollers' life cycle. Because of the extreme operational conditions, the bearings are often polluted, which makes them wear out quickly. The reliable protection of the bearing unit against dust and humidity is the main issue for every roller producer. It is clear that these requirements can be fulfilled by a proper design in the early stage of the entire process. Keeping this issue in mind, the designer should simultaneously consider whether the rollers are suitable for assembly, since it has a great impact on the total production cost. The roller's case is only used as an example for the purpose of this research.

### 3.5.1 Description and redesign of the initial roller

A plant is producing a variety of rollers with different lengths. The roller, which is shown in Figure 3.8, consists of the following details:

* pos.1 - metal hub
* pos.2 - bearing
* pos.3 - sleeve
* pos.4 - lock washer
* pos.5 - sleeve
* pos.6 - axis
* pos.7 - tube
* pos.8 - washer

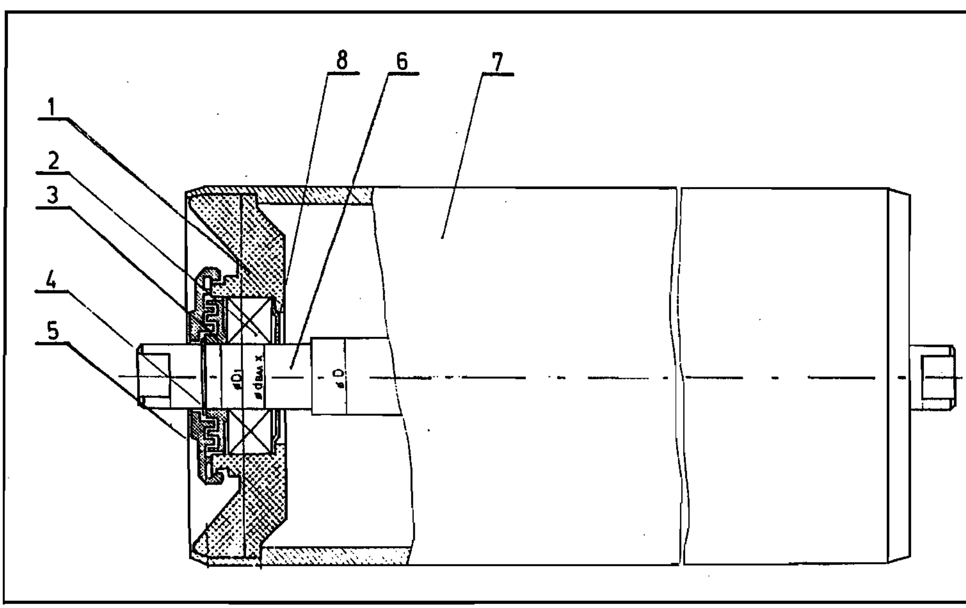



Figure 3.8: The initial roller design.

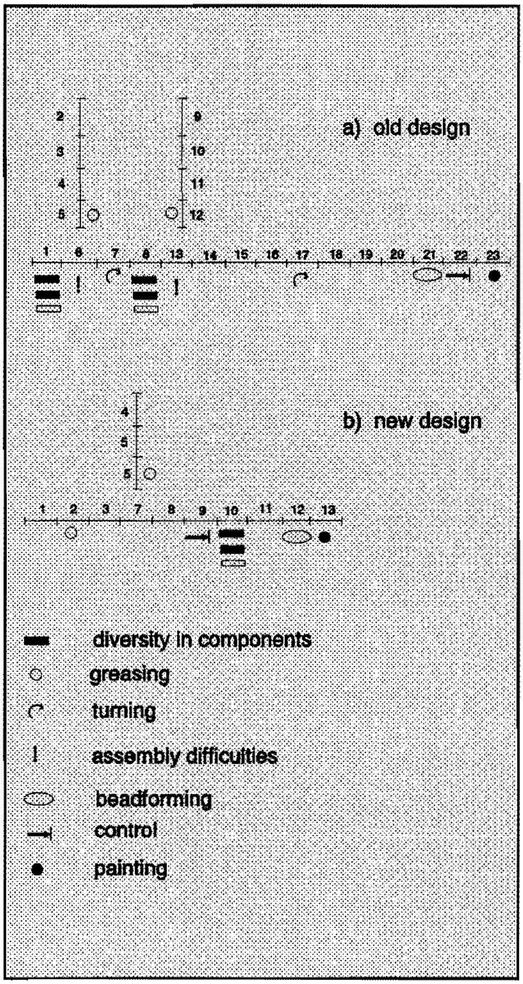



Figure 3.9: Process diagrams.

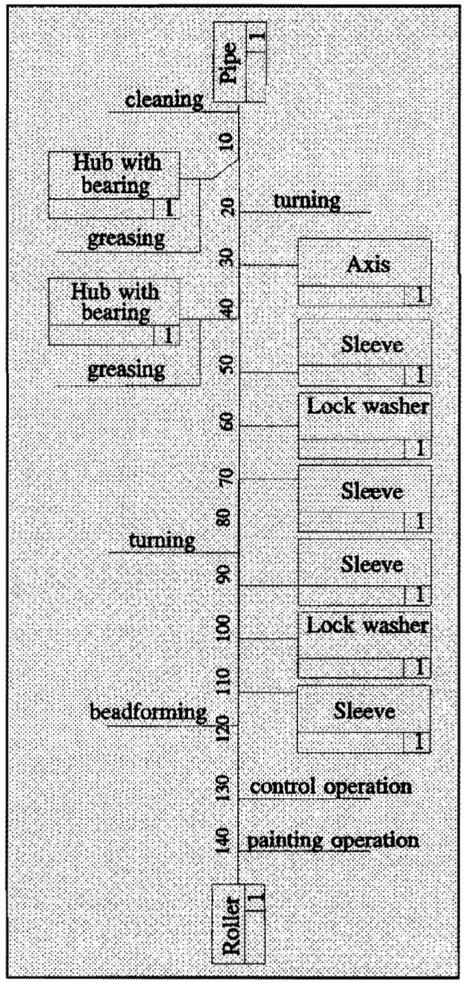



Figure 3.10: The initial assembly process.

The analysis of the initial design brought many disadvantages to light concerning the assembly automation. This can also be seen in the process diagram where the assembly difficulties are represented, see Figure 3.9 (a). Also the complexity of the process is obvious because the roller consists of a lot of details. These details, which are part of the bearing unit, have a complicated shape, which would be troublesome during the orientating, inserting and composing phases. The availability of lock washers (pos.4) makes automated assembly practically uneconomical. In addition, there are technological disadvantages that affect the functionality and quality. It can be mentioned that the bearing unit is not reliably protected. The bearing is located too far from the hanging point causing high deflection during the exploitation and thus quicker wear out. The metal hub (pos.1) is massive (not elastic), and does not allow for compensation of disalignment during assembly and exploitation. The restrictions made during the design stage do not allow the introduction of an advanced assembly process. It is executed manually with a low degree of mechanization. The assembly process corresponding to the initial design is depicted in Figure 3.10. According to the analysis executed with the DFA method, the design efficiency from an assembly viewpoint is 18% (see Appendix 3.1). As regards this low efficiency it has been proven that manual assembly only is justified.

There is no doubt that because of the crucial disadvantages, a new roller design is required. Only in this way the assembly efficiency and the total productivity can be increased. Therefore a comprehensive patent investigation was carried out about the available rollers' design. Based on the obtained results and the requirements concerning the automated assembly a new roller was designed, see Figure 3.11 [Penev, 1989]. It consists of the following details:

* pos.1 - short axis
* pos.2 - hub with bearing
* pos.4 - rubber seal
* pos.5 - cup
* pos.6 - tube

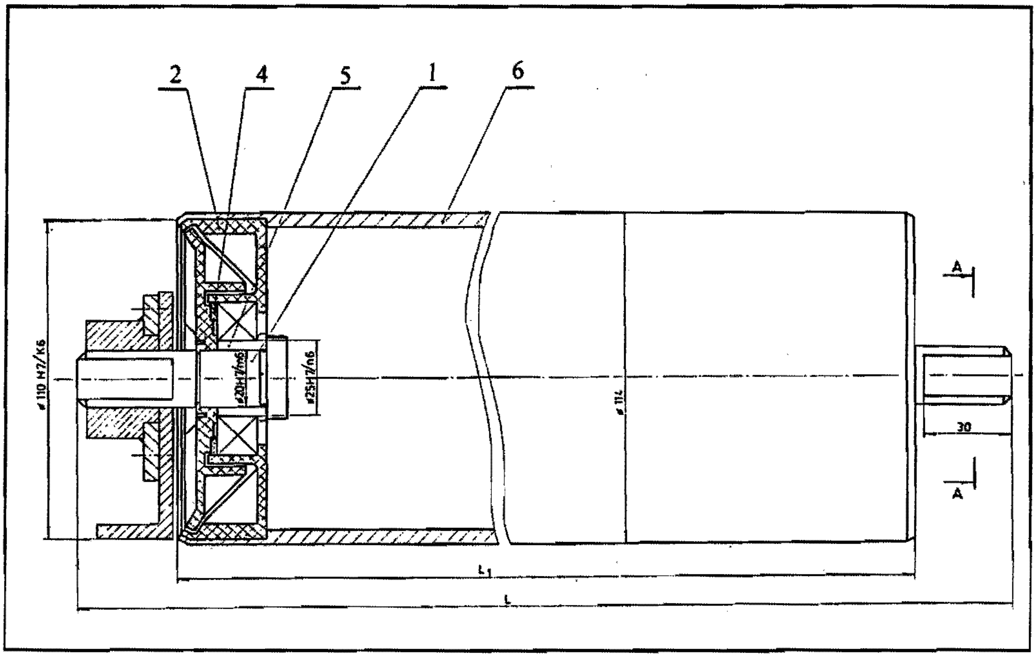



Figure 3.11: The redesigned roller.

It can be seen that a number of details have been removed since their availability is not justified. The choice about which parts should be removed was made by applying the fundamental questions of DFA. In addition, all aspects concerning the improvement of functionality and suitability for an efficient design were considered. This resulted in a new design with a number of attractive features.

First, the *short axis*, which is a completely new solution, can be used for the complete product assortment. It makes it possible to use the bearing unit as a separate sub-assembly suitable for rollers with different lengths. This results in a simplified assembly process, which can be seen in the process scheme, see Figure 3.9 (b). The quantity of materials used also decreased. In addition, the new design allows for the compensation of disalignment. It facilitates the automated assembly since the bearing unit can be assembled separately and joined to both sides of the pipe. Second, the *lock washers* are replaced. In this way details that are definitely unsuitable for assembly are removed. Third, the *bearing unit* consists of a few components that have integrated functions. All details carry necessary functions and their availability is justified. Fourth, the new construction has a *cup* that effectively protects the bearing unit against dust, humidity, etc.

According to DFA, in the early stage of development it should be decided which type of assembly system is the most feasible concerning the particular product design (step 1). As was mentioned before, there are a number of factors that influence the final decision. One of the most important determinants is the investment factor which, in this case, encourages an investment for assembly automation. With respect to this conclusion, the most appropriate assembly system was selected from Boothroyd's chart. It is defined as: *"automatic assembly using free transfer machines with simple programmable work heads (capable of performing several assembly tasks) and manually loaded part magazines; one supervisor and one assembly operator for the machine"*.

After this step was accomplished, it was followed by the evaluation of the design efficiency for manual and automated assembly. It was estimated that the new design efficiency concerning easy of assembly is 40% (refer to Appendix 3.2) against 18% for the old one (refer to Appendix 3.1). In addition, the efficiency for an automated assembly was estimated at 35%. Within this step the corresponding assembly process had to be developed, see Figure 3.12, and the related cost had to be calculated, including handling, checking, composing and the other involved processes. From the chart in Appendix 3.2 one can see that further reduction of the number of components is not justified. This conclusion follows from the answers to the fundamental questions. This means that an additional change in the roller's design is not rational any more. The product is friendly from an assembly viewpoint and the concurrent development of the assembly process and the corresponding system can be continued.

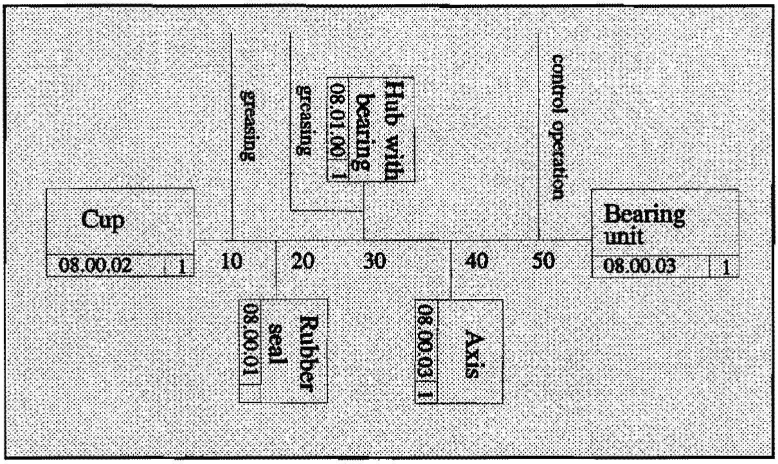



Figure 3.12: The new assembly process.

### 3.5.2 Systematic development of an assembly system for rollers

The design process was structured and executed in a systematic way. The first stage of this model, the **clarification of the task**, was accomplished with the application of DFA for analysis of the initial roller's design. At the end of this stage, the most feasible assembly system was selected. It should be mentioned that the result obtained from the analysis should not be regarded as a restriction. In the final assembly configuration, small changes are not excluded. Applying the theory of technical systems and the systematic design approach, the assembly system components and their relationships were set regarding the product design and the corresponding assembly process.

The **conceptual design** should end with the generation of a number of alternatives. In this case, four configurations were suggested [Penev, 1989]. Using different criteria one of them was selected. The lay-out of the selected configuration is given in Figure 3.13. It consists of four positions for the automated assembly of the bearing units. The final assembly was accomplished off-line in a semi-mechanized work position.

During the **embodiment design** every work position and the required associated equipment were drawn and worked out.

In the last stage **(detailed design)**, the carriers, pneumatic units and grippers were designed. With this step the entire development of the automated assembly system was accomplished.

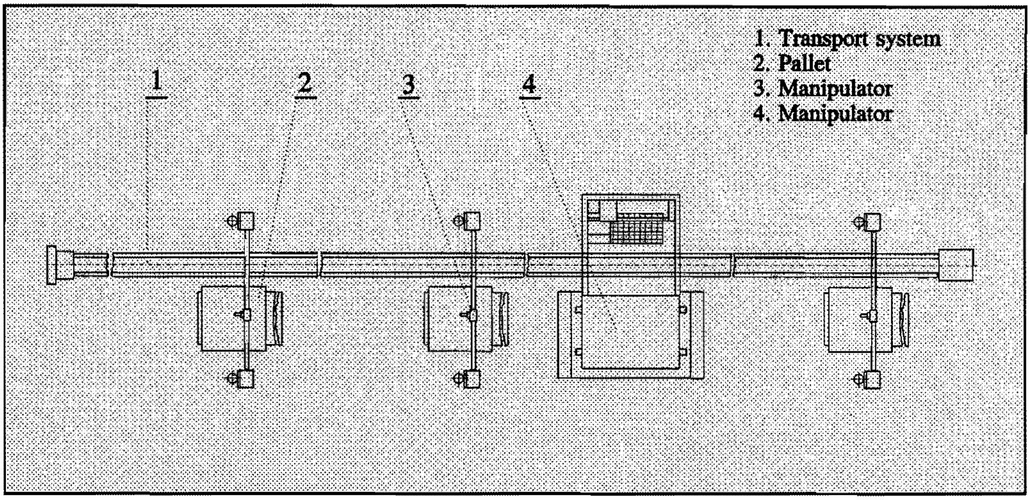


Figure 3.13: Arrangement of an automated assembly system for rollers.

Let us take a look at the advantages of the new roller and their influence on assembling and possible disassembling. First of all, the number of parts was considerably reduced, which had an impact on the operational time. The lock washers were removed by integrating their function with other components. This also facilitated disassembly since lock elements are totally unfriendly for disassembly. Furthermore, the bearing unit is an individual sub-assembly which makes it easy for disassembly and reuse. The parts involved in the bearing unit are made from recyclable materials. For instance, the cup for protection of the bearing is produced from a plastic material, which can be recycled in an environmentally friendly way and then reused. After a cleaning operation, the short axis can be introduced in the assembly process for all type of rollers. These advantages confirm the assumption that considering the assembly and disassembly issues in the early design stage has a great impact and facilitates the reuse of products.

## 3.6 The necessity of special developments in disassembly

Although disassembly and assembly are similar processes, there are particular differences between them that should be considered. This implies that not every solution in assembly can be used to accomplish disassembly issues. For this purpose new specific solutions should be found. They have to be related to the three disassembly variables: discarded goods, disassembly process and system.

First, new solutions should be found for the identification of the discarded goods. Since the input flow of disassembly systems is random, a rapid determination of the discarded good's structure is required. The number of desired and poisonous components and materials, and their location within the entire structure has to be defined. This requires an advanced information system able to provide all necessary data concerning the nature of the input flow of discarded goods. To develop such a system, the information obtained from the producers and during the disassembly process has to be stored in a data base. It has to include all the information required for the analysis and determination of the disassembly strategy. For instance, the structure of a discarded good can be represented by means of pictorial drawings that clearly display the exact joints and a number of components. In this way, the operator is able to carry out the disassembly operations by means of appropriate tools. When considering automated machines and industrial robots, the information can be used to activate the corresponding software program, which controls the robot system. In this way, the efficiency and flexibility of the disassembly process can be considerably increased. In addition, other solutions are required for identification of the various compounded materials included in the input flow. For instance, the wide variety of plastics can not be recognized by a human operator. In this case, special equipment is required that reliably determines the various plastics.

While designing the new generation of green products, all disassembly requirements should be involved in the early design stage. This means the development of software tools for the design of disassembly friendly products. In other words, the aspects of disassembly should be involved in the current computerized versions of concurrent engineering methods.

Second, concerning the development of a disassembly process, a reliable method is required for the determination of the disassembly strategy. It should include the number of competitive disassembly plans, the most feasible way for it to be carried out and a decision criterion about the stage that the discarded goods are sent to a shredder for material recycling. It should be emphasized that the disassembly strategy is different concerning the various input flows. Moreover, it is a flexible issue that may be altered very often as regards the market-oriented requirements. This means that a flexible method is needed that can represent a comprehensive and flexible disassembly strategy. After such a method is developed, a software tool should be created to facilitate the determination of the disassembly strategy. In addition, after shredding, the compounded materials should be separated for reuse. In this context, new techniques are required to separate materials of the shredding fractions as much as possible. Also, technologies for the reprocessing of various materials in the most efficient and environmentally sound way should be developed.

Third, concerning the design and arrangement of disassembly systems, new disassembly tools and machines for special purposes has to be developed. The aim is to facilitate the current labour intensive process and to achieve higher productivity and efficiency.

Generally, a systematic design approach should be developed for disassembly purposes, which involves the issues discussed above. It should be comprehensive, involving many important aspects like product life cycle, marketing, legislation rules, integral design, etc. The purpose is to improve the current disassembly facilities and to achieve valuable results in this field in due time.

## 3.7 Conclusions

The design of disassembly systems is not a single process but rather a market-design integrated process. At present disassembly is at the beginning of its development. To promote this significant issue and to ensure satisfactory results, knowledge and experience is required concerning the topics of engineering design. For this purpose design skills should be developed based on engineering design that can contribute significantly to disassembly.

Integrating different design techniques into a systematic design approach would result in an important procedure used by a designer to reach the desired goals in any field of engineering design. Because the design process is an intellectual process, which contains many operations of varying character and complexity, it should be executed systematically. The link with the other segments of engineering design and fundamental science is also vital. Nevertheless, it should be recognized that the entire design process involves creativity as a unique human element. However, the study of design and application of the appropriate methods in the right phase can contribute significantly to the accomplishment of those goals. In this context, it is emphasized that design is a learning process and efforts must be devoted to the creation of design skills and the development of design knowledge. Moreover, the development in engineering design is a continuous process and it will never end. New methods with the combination of advanced software tools are available and are expected to be introduced. They support the work of those designers who are aware and have comprehensive knowledge of the engineering design and its segments.

During the analysis of the entire disassembly process, which is a part of engineering design, it has been found that it has common features and requirements with assembly. Designing for assembly also means promoting disassembly to some reasonable extent. This is the reason that these two comparable processes should be considered simultaneously, together with the other important design aspects. The applicability of DFA as a tool for the proper design of a product and the corresponding assembly system has also proved to have consequences for disassembly. In addition, the benefit of the DFA method has been demonstrated with a practical case. It clarifies that this technique is suitable for the concurrent design of a product, process and system. Based on the results, it can be concluded that the assembly process and the methods that systematically support its development are significant for disassembly. This is the argument that they have to be studied and understood by the designer in order to apply them concisely and wisely in practice. One can be assured that the proper usage of these methods can significantly contribute to efficient production, assembly and possible reuse of products and materials. Finally, it can be deduced that assembly is an indispensable part of the entire production process, having a big influence on disassembly and on the level of mechanization and automation of the corresponding system. This means that the design of new products should be based on methods that simultaneously involve all aspects of the product life cycle. In this view, assembly and disassembly are indispensable and should always complement each other. This will allow the design of recovery friendly products as well as advanced assembly and disassembly systems.

# Chapter 4

# Determination of a disassembly strategy

## 4.1 Introduction

The technological developments within the manufacturing industry were not followed adequately by the recycling industry. In the past, the manufacturers devoted all their efforts to improve the performance of the production processes and systems without considering the recovery options. Because of a lack of recovery considerations and a lack of recycling (disassembly) friendly products, a huge amount of discarded goods will have to be processed that are unsuitable for reuse. The recovery is currently limited to some materials, which are usually obtained by a shredding process. However, this option is not feasible in every case, especially when complex discarded goods have to be processed. To increase the recyclability of the compounded materials, a disassembly process has to be applied. The aim of disassembly is to achieve a maximum recovery percentage from the discarded goods which not only contain desirable materials and components but poisonous ones too. If these are in the output flow, the recyclability of the discarded goods would be considerably decreased; therefore these fractions should be removed. In addition, to increase the financial net result of recovery, the desired output flow should contain materials and components that generate a positive cash flow; therefore they have to be removed too.

When dealing with disassembly, the designer cannot influence the input flow as this contains the discarded goods that can not be redesigned. Therefore, the particular input range and desired output flow should be considered when designing disassembly systems. For this reason the discarded goods should be analyzed and described from a disassembly and recycling viewpoint. The discarded goods can be represented as a set of components with a number of relationships between them. The first stage of the analysis process is the establishment of a distinct structure, which represents the discarded goods. This can be achieved by a "tree" graph in which all relevant components and materials, and the physical relations between them are displayed. In such a graph structure, one can find which components and/or materials are significant for the determination of the desired output flow. In this context, three categories of components (materials) should be considered:

a) Components (materials) that should be compulsorily removed because of safety requirements.
b) Components (materials) that should be removed because of the legislation rules and environmental requirements.
c) Components (materials) that are considered valuable and should be disassembled because of economic issues. Such fractions influence the purity of the output flow and determine the profit.

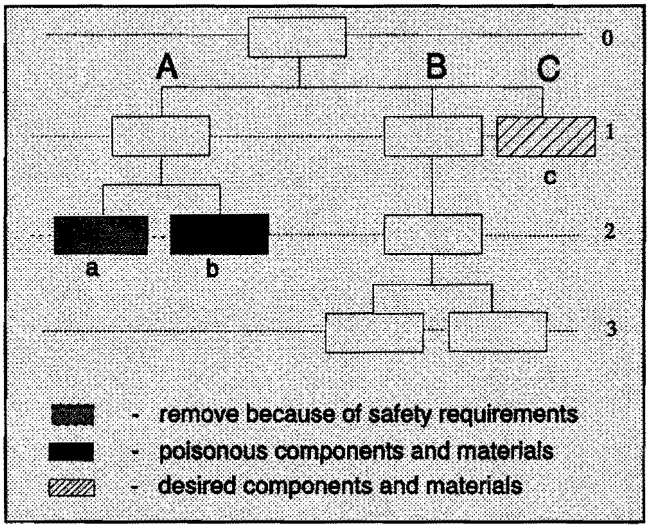



Figure 4.1: Possible structure of a discarded good.

In the ideal situation, a choice should be made as to which fractions should be removed and in what sequence, so that the highest profit can be generated and the legislation requirements can be fulfilled. However, in practice the physical and geometrical relations among the parts limit the order of operations in disassembly. For instance, Figure 4.1 denotes the distribution of components in a discarded good and which of them should be compulsorily removed because of safety (a) and environmental (b) requirements. In addition, it gives a valuable component (c) that should be disassembled in order to increase the net result. To disassemble the poisonous component in level 2, it is obligatory to pass level 1 of cluster A. This is required because there are no physical connections between level 0 and 2. However, the valuable component in level 1 of cluster C can be disassembled without proceeding through all levels. The remaining components in cluster B are not important for the generation of high profit, therefore they are not disassembled because that would only result in high costs. This means that the corresponding disassembly operations can be shunted if they are not justified from an economic viewpoint. In this context, the poisonous components and materials define the number of compulsory disassembly operations, while the valuable ones imply the number of desirable operations.

Once the structure of the discarded goods has been clarified, it will be found that not every disassembly operation is possible. Some operations are not possible because there are no physical relations between the components, and others because the joints are fixed (welding, soldering, etc.) and no physical separation is possible. As was explained in the previous chapter, disassembly is not the reverse of assembly and many operations can be omitted if they are not profitable. In other words, after fulfilling the safety and environmental requirements the process should be terminated as soon as the disassembly costs are higher than the revenues. It is clear that further disassembly is not feasible because of economic considerations. To reduce the time and costs of disassembly, destructive methods are allowed for a more rapid disassembly of a desired part; this is achieved by dismantling. During this process, a number of materials streams appear. Afterwards the discarded goods are sent to a shredder for material recycling. In this way, the recovery of the discarded goods can be optimized by application of the most feasible option; this will be clarified in this chapter.

Obviously only the disassembly of goods to some feasible economic extent can result in a high percentage of material recycling and reuse of components and subassemblies. This means that the goods have to be disassembled according to a disassembly strategy. It determines how the goods should be processed in order to obtain the highest economic result under the constraint that some minimum recovery percentage is reached. In this context, the disassembly strategy is the result of an optimization problem where the net result of the activity is maximized. This can be expressed by:

$$\max_{r > r_{min}} P(r) = R(r) - C(r) \qquad \textbf{(4-1)}$$

where:

| | | | |
|---|---|---|---|
| where: | P | = | net result (profit) |
| | R | = | total revenues from recovery |
| | C | = | total costs |
| | r | = | proportion of recycled materials |
| | $r_{min}$ | = | required minimum proportion of recycled materials |

To fulfil this optimization issue, a disassembly strategy should be created that involves considerations about the optimal disassembly process to be applied. Such a strategy should include the following issues:

1) Generation of all feasible disassembly plans (see section 4.2).
2) Determination of the profits for the generated disassembly plans (see section 4.3).
3) Determination of the optimal disassembly plan and depth with respect to total costs and revenues (see section 4.4).

In general, a disassembly strategy gives a plan indicating which disassembly operations should be carried out to recover the discarded goods in the most feasible way according to the established requirements. Therefore, the determination of the disassembly strategy is considered an economic issue, which is significant for the design of disassembly systems. This task requires a systematic approach, which implies that suitable methods and theories should be used. In other words, the problem of disassembly has to be transformed into a similar one in order to make use of the available knowledge and experience. However, it is obvious that disassembly has its own features and requirements, which should be solved in a particular way. For this purpose the available techniques related to this subject will be interpreted from a disassembly viewpoint and extended with particular issues. The following sections of this chapter will be devoted to the development of a comprehensive method for the establishment of a disassembly strategy.

## 4.2 Some methods for the generation of disassembly plans

The generation of the disassembly sequences can be regarded as disassembly process planning. It gives a number of operations that should be executed to obtain the desired output flow. Planning and scheduling problems may be approached from a number of different perspectives. Various methods are used to solve scheduling problems. Some of these methods are compatible, others serve particular issues. As disassembly is a new process, it is unrealistic to expect that there will be a scheduling method that completely fulfils the requirements for the establishment of a disassembly strategy. It is supposed that while making use of the available scheduling methods, a new method is required that involves the new particular disassembly requirements. The aim of this section is to clarify which of the available scheduling methods can be used as a basis for disassembly process planing and what should be further developed.

### 4.2.1 Generation of the disassembly plans by using the assembly plans

One of the widely used approaches for scheduling, generation and selection of disassembly plans is related to the generation of the assembly plans. In Chapter 3, the assembly process has been described in detail and its link to disassembly has been highlighted. The idea to consider them simultaneously arises because many problems related to the determination of assembly sequences are transferred into the determination of disassembly orders. For instance, one of the widely used methods that automatically determines the assembly sequence using feature based CAD is based on the following assumptions [Molloy, 1991]:

- o Disassembly is a process in which every part can be removed from the assembly structure without collapsing it.
- o Assembly is the reverse process of disassembly.

Based on the above, four steps have been determined to find the disassembly sequences. The following steps are included:

1) Grouping of components with respect to a presumed moveable component.
2) Determination of possible moveable directions of each component.
3) Determination of the disassembly directions of each component.
4) Identification of the disassembly sequence by examination of the disassembly directions.

In this method the components are represented by their boundary representations and relationships in an assembly and specified by the mating conditions between all the components. The disassembly sequence problem is solved by the determination of the moveable directions of each component. In addition, a check is made to see whether the component can be removed from the structure without a collision. The software program developed chooses every component randomly and decides if it can be disassembled. If a disassembly level is completed, the remaining components are rearranged into a new subassembly which is then considered as a new leaf in a disassembly tree. Then the algorithm is applied to every subassembly until all components are disassembled. From the disassembly graph created by executing the reverse operations, an assembly graph can be deduced which consists of the assembly sequences.

The assumption that assembly can be regarded as the reverse of disassembly has been used by other authors to execute a study on the automatic generation of assembly and disassembly sequences [Sekiguchi, 1983]. They consider disassembly as the change of the position of the parts and the corresponding connective relations. The connective relations are derived from the assembly drawings of machine units and arranged into fit and contact groups. On the other hand, they are subgrouped with respect to their degree of disassembly difficulty which is determined by the combination of the freedom of motion and the required force to change the relative position of a part in order to accomplish the disassembly process. Based on the connective relations, a selection is made as to which part should be removed from the machine unit and in what direction. The disassembly sequences proceed until all parts or subassemblies are removed. The reverse sequence of the disassembly operations generated are found to be practically as effective as the assembly sequences. In this context, the above-mentioned methods are suitable for the generation of the assembly sequences, where all operations should be accomplished according to the process requirements. However, this is not the case with disassembly where a number of operations can be omitted. In addition, there is a lack of economic considerations about the optimal disassembly plan and depth. Thus, the aforementioned methods do not fulfil the requirements concerning the establishment of the disassembly strategy, which involves economic issues.

### 4.2.2 AND/OR graph method

An advanced method for the creation of mechanical assembly sequences has been developed by Sanderson [1987, 1991]. The problem of generating the assembly operations is transferred into the generation of the disassembly operations. This method is based on a graph that represents the assembly orders, the so-called AND/OR graph. It is considered a systematic procedure that guarantees that all feasible sequences will be generated. A decomposition approach is used to solve the disassembly problem. The expression "disassembly task" is regarded as the reverse of a feasible assembly task. Every decomposition corresponds to a disassembly task. By looking at all decompositions of the assembly, all the ways by which the disassembly can be split into two subassemblies can be found. This approach leads to an AND/OR graph representation of the disassembly sequences and the corresponding reverse assembly sequences. Figure 4.2 represents an AND/OR graph for the depicted simple product. The nodes in such a graph correspond to the number of components or subassemblies. The top node, which has no ancestor, corresponds to the whole assembly. The nodes which have no descendants, correspond to the individual components. The arrows are directed and represent the disassembly operations. It should be emphasized that such a graph has no cycle. In other words, after a stage has been achieved no return is possible to the previous one. In addition, nodes that correspond to assemblies that contain only one part are the terminal nodes. This approach can be considered a step towards the development of a systematic procedure for the generation of all feasible disassembly sequences and should be considered when regarding disassembly issues.

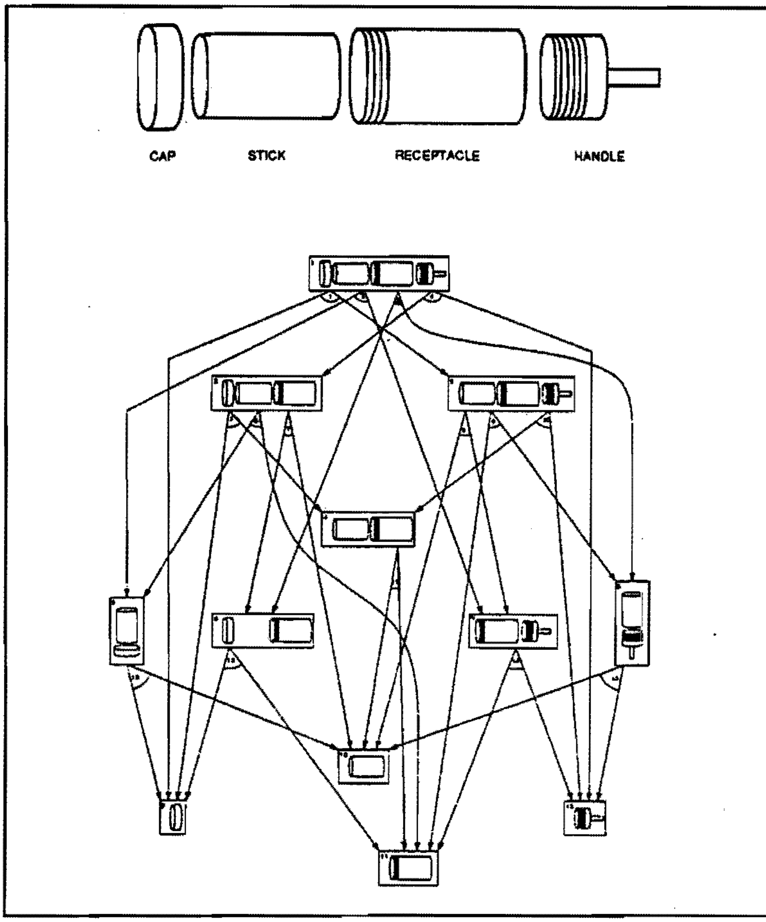



Figure 4.2: Disassembly sequences represented by an AND/OR graph [Sanderson, 1991].

### 4.2.3 Generation of the disassembly plans by using boundary representation of an assembly

Other authors have described different methods for the representation and generation of disassembly sequences. An algorithm to develop a disassembly tree that yields a minimal sequence of linear motions for a robot was presented [Woo, 1987]. To construct the disassembly tree, the data structure used by the algorithm is described. It gives an assembly that consists of a number of components {a,b,c,d,h,f} as a boundary graph. It consists of vertices, edges and faces that are used as elements to describe the assembly. Every face, which represents a surface from a component, consists of a number of edges. On the other hand, an edge consists of two vertices. In this way, a component can be described by its faces (surfaces), edges and vertices, see Figure 4.3. For instance, the component *f* is described by its four vertices $v_1$, $v_2$, $v_3$, and $v_4$, which are elements of the corresponding edges $e_1$ and $e_2$. In addition, an edge that is common to two faces is called a mating edge. For instance, the edge $e_1$ is a mating edge of the faces *h* and *f*. In the case that an edge ($e_2$) belongs to only one face (*f*), it is called a boundary edge.

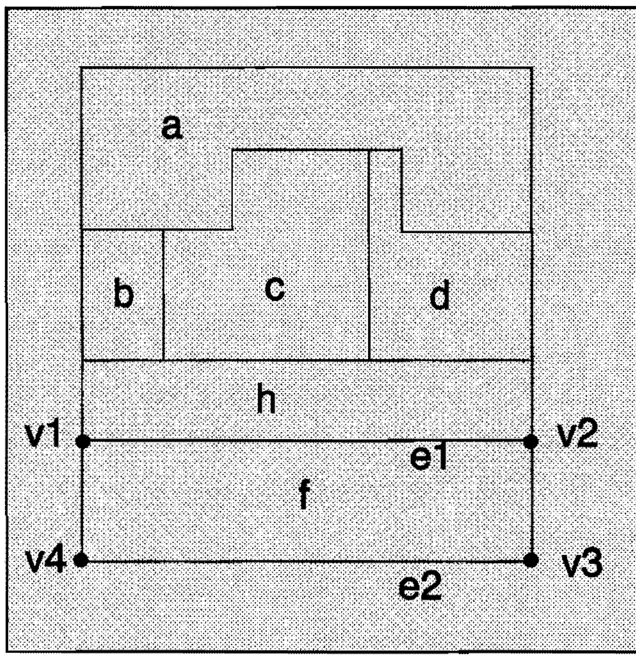


Figure 4.3: Boundary representation of an assembly.

The generation of the disassembly tree begins by determining whether components with boundary edges can be disassembled. Every component is tested for disassemblability with respect to a subassembly. The ones found to be fit for disassembly are attached to the disassembly tree as nodes. The process continues until the nodes equal the total number of components. This method gives a minimal sequence of a single component that should be removed. It is used to evaluate the design for easy robot assembly and disassembly for maintenance and repair. While this method is useful for automated disassembly, it fails to provide an answer to the problem of the optimal disassembly strategy, since all components should be removed and no economic considerations are involved.

Similar algorithms investigate procedures that can be used to assess service difficulties and costs at the early stages of the product design [Subramani, 1991]. For this purpose the concept of a disassembly diagram has been introduced. A disassembly diagram represents a model for an assembly that straight-forwardly facilitates the generation of optimal disassembly sequences for all the parts through the application of a systematic procedure. The model contains knowledge about the disassembly precedence of various parts in the different directions of disassembly. To create the disassembly diagram, two main procedures are used:

- o Set-list procedure - it gives the minimum numbers of disassembly directions along which a part can be moved with respect to its neighboring parts.
- o List-contact procedure - it gives a list of all joints that need to be broken in a given direction.

Applying these procedures to each part results in the generation of the disassembly diagram. The algorithm starts with parts that can be removed immediately. These parts are attached to the disassembly diagram as free nodes. By continuing with the disassembly of free parts, the other nodes are generated. They contain information about the disassembly sequences of parts and the total time and cost. This method is similar to the previous ones in the sense that all parts should be disassembled. The present procedure does not consider destructive techniques, which can break several contacts simultaneously and reduce the disassembly times. Therefore, this method is useful for accomplishing service and repair tasks. However, it would have a limited application for the recovery of consumer goods where not every operation should be carried out.

### 4.2.4 Using a "sweeping" table for the generation of the disassembly sequences

For complex assemblies a new algorithmic approach for the generation of a disassembly plan, which includes disassembly directions as well as disassembly sequences, has been introduced through freedom and interference spaces for the following cases [Lee, 1992]:

1) Full disassembly and assembly.
2) Part replacement by individual disassembly.
3) Part replacement by group disassembly.

This method suggests that disassembly of a particular part from an assembly depends on the degree of freedom and the degree of interference that is acting on that part by the others parts. The required information can be found in a matrix that contains the degree of freedom of the elements in the first column. On the other side, the first row gives the number of components in the assembly to be disassembled. In addition, a value in a cell represents which parts and in what directions should be disassembled in order to reach and remove the part from the top cell of the same column. Such facts are summarized for each part and for every direction. This is used to create a "sweeping" table that contains the degree of freedom and degree of interference of each part, see Figure 4.4. For instance part *d*, which can be found in the first row of the sweeping table, represents a component (part) from an assembly. To disassemble this part, the information given in the corresponding column should be considered. In this context, the part *d* can be removed in the following ways:

1) By removing the parts {a,b} in direction L (Left).
2) By removing the parts {a,b,c,g} in direction U (Up).
3) By removing the parts {b} in direction R (Right).
4) By removing the parts {e,f} in direction D (Down).

| Direction \ j | a | b | c | d | e | f | g | h |
|---|---|---|---|---|---|---|---|---|
| L (left) | egh | acde fgh | abg | ab | abh | b | • | • |
| U (up) | bgh | a | abg | abcg | abcd gh | abcd egh | ac | ag |
| R (right) | bcde | cdef | b | b | ab | b | abc | abe |
| D (down) | bcde fgh | acde f | defg | ef | f | • | acde fh | aef |

Figure 4.4: Sweeping table [Lee, 1992].

Once the sweeping table is created, the disassembly sequences can be generated. This is done by first removing parts that have a 'nil' (•) in their columns. This represents a direction that is free and the part can be removed from the assembly without a collision. For instance, in Figure 4.4 it can be seen that parts *f*, *g* and *h* can be disassembled first, because they have 'nil (•) in their columns. After execution of these operations some parts will be removed and new directions for possible disassembly will occur. The resulting table after removing of *f*, *g* and *h* contains information about what can be removed next. This process continues until all parts are removed and results in disassembly sequences, which are represented by a disassembly tree.

### 4.2.5 Conclusions

The disassembly methods discussed above only cover a limited part of the entire process. These methods give the possible disassembly sequences from a structural and technical viewpoint. In this context, there are no considerations about the application of destructive disassembly techniques and the shredding option. This means that they do not provide information about the optimal disassembly plan, which should give a clear presentation of the most feasible sequences and to what extent disassembly should be proceeded with. From the disassembly methods reviewed, it can be concluded that the AND/OR graph best suits our needs regarding the determination of the number of disassembly plans. It is the most logically complete description of the disassembly that can be used for sequence generation. In addition, it gives us the opportunity to use the dynamic programming's power to determine the optimal plan when a particular disassembly case is considered. This is a search problem and criteria should be found to select the best alternative, which implies a solution with minimum costs. However, disassembly operations that do not contribute to obtain the desired output flow should not be performed. This implies that after the termination of the compulsory and desirable operations, one should only proceed with disassembly if it is economically profitable. Whether this action should be taken and the discarded goods should be sent to a shredder depends upon economic considerations, which are not involved in the methods discussed above. It is required to find an evaluation function to guide the search process and to make an efficient choice of feasible disassembly plans and disassembly methods among the many alternatives.

## 4.3 Determination of the profits at every recovery level

The aim of disassembly is to reuse the discarded goods in the most profitable and environmentally sound way. By using the AND/OR graph suggested by Sanderson [1991], all feasible disassembly plans can be created. Then, the profits of every recovery operation should be determined in order to provide the required information for the selection of the optimal disassembly plan. This section suggests how to approach and solve this problem.

In practice, the recovery dilemma can be simplified by means of shredding, which reduces the number of disassembly steps. For instance, this is the case with respect to consumer goods when all poisonous components and materials are removed, and applying disassembly operations does not contribute to the generation of higher revenues or decreasing the disposal costs. When disassembly can be replaced by shredding depends on which process is more profitable. In this context, recovery can be regarded as a process that includes a number of sub-processes like:

- Service.
- Disassembly.
- Dismantling.

- o Recycling.
- o Disposal.

Each of these processes represents a different recovery level. Which level has to be chosen depends upon the desired output flow. Besides service, which is regarded as a special recovery task, the other options are possible at each stage of the disassembly strategy. To decide which of them has to be applied, considerations should be made concerning the following issues:

- o What is the present value of the discarded goods and materials?
- o What is the recovery cost per operation?
- o How should the legislation rules be met with minimum costs?
- o How should the environmental impact be reduced with minimum costs?

As can be seen, a decision should be taken based upon a number of economic considerations related to the value added to products and discarded goods, which is expressed in money.

When regarding recovery, various revenues can be generated. In this context, the profit P from disassembling or dismantling that is applied to obtain the desired output, can be expressed by:

$$P_{dis} = \sum_{j=1}^{m} ( R_j - C_{dis,j} ) \quad \textbf{(4-2)}$$

and:

$$P_{dm} = \sum_{j=1}^{m} ( R_j - C_{dm,j} ) \quad \textbf{(4-3)}$$

where: $m$ = number of valuable components
$R_j$ = revenue of component j
$C_{dis,j}$ = disassembly costs of component j
$C_{dm,j}$ = dismantling costs of component j

On the other hand, the profit from shredding to recover materials can be given by the following equation:

$$P_{shr} = M.\sum_{j=1}^{k} (r_j.\alpha_j) - \sum_{j=1}^{k-1} C_{sep,j} - C_{shr} \quad \textbf{(4-4)}$$

where: $k$ = number of material fractions
$M$ = mass of the shredding part of the good (subassembly)

| | | |
|---|---|---|
| $r_j$ | = | revenue of a material fraction (negative if the material must be dumped) |
| $\alpha_j$ | = | the mass of a fraction compared to the total mass of the shredding part |
| $C_{sep,j}$ | = | separation cost of a material fraction of the shredded part |
| $C_{shr}$ | = | operational cost of the shredder |

In eq. (4-4) $\alpha_j$ is the relative mass of a material fraction:

$$\sum_{j=1}^{k} \alpha_j = 1 \quad \alpha_j > 0 \quad \forall \alpha$$

In addition, the separation cost is split per material fraction while the operational cost of the shredder is common for the whole material volume to be processed, as experienced in practice.

Consider the following example, where a discarded good consists of two materials: ferrous and plastic. This good should be recovered so that maximum profit can be generated. The profit that can be obtained from a subassembly is either the profit from disassembling ($P_{dis}$), the dismantling profit ($P_{dm}$) or the profit of the recycled material ($P_{shr}$). In this context, $P_{dis}$ is the profit from the recovery of the components $r_1$ and $r_2$, which either contain plastic or ferrous fractions. In addition, the profit can be given by $P_{dm1}$ and $P_{dm2}$, which stand for the recovery of one fraction as a component $r_1$ ($r_2$) and the other as a material fraction $m_2$ ($m_1$). Finally, $P_{shr}$ gives the profit from recycling, which implies the recovery of the fractions as materials; component recovery is excluded in this case. This can be expressed as making a choice among four alternatives and selecting the best recovery option :

$$P_{max} = \max\left(P_{dis}, P_{dm1}, P_{dm2}, P_{shr}\right) \qquad \textbf{(4-5)}$$

where:

| | | |
|---|---|---|
| $P_{max}$ | = | maximum profit |
| $P_{dis}$ | = | profit from disassembling |
| $P_{dm1}$and $R_{dm2}$ | = | profit from dismantling |
| $P_{shr}$ | = | profit from shredding |

To obtain the maximum profit from a discarded good, the most feasible recovery option should be chosen. This depends upon economic considerations that are represented by the above equations. We shall clarify what conditions should be fulfilled in every stage in order to apply the most profitable recovery option, see Figure 4.5.

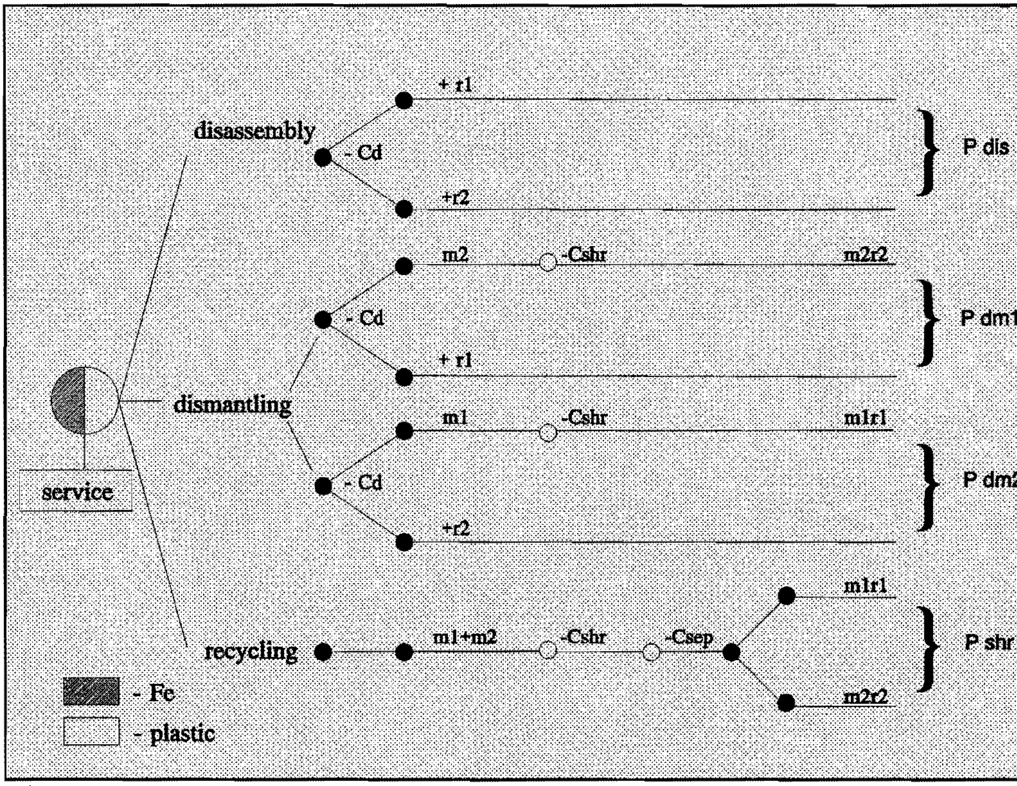



Figure 4.5: Recovery options.

**Service** is regarded as a segment of the entire disassembly process. Its main task is to reuse the complete discarded good by replacing a single or a few components. Such a policy is feasible if the performance of a good can be recovered to its initial state by a small investment. Following that, the good can be sold to a secondary market. To apply service the money value of the good after reparation (remanufacturing) must be higher than the sum of the total cost and the theoretical value before service. This condition is met if:

$$V_{pr} > V + C_{dis} + C_{as} + C_c + C_m \qquad \textbf{(4-6)}$$

where:

| | | |
|---|---|---|
| $V_{pr}$ | = | money value of the good after repair |
| $V$ | = | money value of a discarded good before repair |
| $C_{dis}$ | = | disassembly costs to replace a component |
| $C_{as}$ | = | assembly costs |
| $C_c$ | = | price of the replaced component |
| $C_m$ | = | miscellaneous costs |

If this requirement is fulfilled the service task is justified. Otherwise one should proceed with the following disassembly level.

**Disassembling** is a non-destructive technique and implies the extraction of the desired and poisonous components and/or materials. The most feasible plan to achieve this goal can be found by using the AND/OR graph. At this point, a decision should be taken whether to continue with disassembling or to send the discarded good to a shredder. In this context, proceeding with disassembly is justified if at a certain stage the following equation holds:

$$P_{dis,i} > \max\ (P_{dm,i}\ ,\ P_{shr,i}) \tag{4-7}$$

**Dismantling** is a destructive technique. It implies less precise and expensive disassembly. By applying dismantling, a discarded good can be broken down faster and with less costs. The following condition should be fulfilled:

$$P_{dm,i} > \max\ (P_{dis,i}\ ,\ P_{shr,i}) \tag{4-8}$$

In this case, proceeding with dismantling is also justified if more pure fractions can be obtained that are more valuable.

**Recycling** is associated with the reuse of materials. In the aforementioned selection, it has been found that for a lot of goods the components do not have a high resales value and only material reuse is justified. Therefore, these discarded goods are sent to a shredder. For the execution of this process, the following equation must be valid:

$$P_{shr,i} > \max\ (P_{dis,i}\ ,\ P_{dm,i}) \tag{4-9}$$

If this condition is met, after the poisonous and valuable fractions are removed, there is no need to generate and further consider disassembly steps. However, it is important to define to what extent one should proceed with the separation of the shredded materials. It is suggested that as soon as the costs for recycling are higher than the revenues, the process should be terminated. This process is considered to be a function that decreases continuously. In other words, continuing with recycling will never provide higher revenues. The problem is similar to finding the optimal level of disassembly. This implies that the revenues of recycling given in formula (4-4) must be positive.

**Disposal** is the last stage of disassembly in which no revenue is generated. However, it has influence on the whole process since in this stage the environmental issue can be judged. As was stressed before, the taxes for disposal have been increased drastically. This fact will push companies to deal with disassembly not only to generate positive revenues from discarded products, but also to decrease the costs for their dumping. This means that the price for disposal is higher in comparison with all other costs associated with disassembly. Although in some cases revenues can not be generated, disassembly will be justified if the disposal costs are higher than the recovery costs plus the disposal costs for the remaining fractions:

$$C_{dp} > (C_{rec} + C_{dp,a}) \tag{4-10}$$

where: $C_{dp}$ = cost for disposal of the good without recovery
$C_{dp,a}$ = cost for disposal of the remaining part of the good after recovery the valuable fractions (decreasing the negative revenues)
$C_{rec}$ = total recovery costs

This means that by recovery it is possible to reduce the total disposal taxes. This can be achieved by removing materials for which a penalty has to be paid if they are dumped.

By utilization of the suggested approach, the profits of every disassembly plan can be determined. Every disassembly plan consists of a number of operations. Each operation implies a recovery option that is applied to obtain the desired output flow. At every stage of the process, the most feasible recovery option should be selected. Now a method is needed that can select the optimal disassembly plan among the alternatives and when the disassembly operations should be terminated. This issue will be worked out in the following section.

## 4.4 Determination of the optimal disassembly plan

After the feasible disassembly plans are generated (see section 4.2) and the recovery profits per disassembly step are determined (see section 4.3), the optimal disassembly plan that fulfils the established requirements has to be found. This task is the most important issue related to a disassembly strategy and it tells us which disassembly plan will generate the desired output flow. As was shown before, the disassembly process can be represented by a number of steps (operations) and the corresponding relationships between them. Our task is to find the most efficient and economic manner to accomplish the disassembly process. This can be regarded as finding the cheapest way to move from one point to another with regard to the cost function (4-1). In practice, similar problems are solved by the utilization of graphs. Graphs can be found in many fields such as engineering, topology, physics, economics, operational research, etc. They usually represent a structure of a system, process, product, organization etc. Graphs can be considered an abstraction of the reality. Nowadays the theory of graphs is used as a powerful tool to analyse various problems. In this case, it will be shown how graphs and the method of dynamic programming can be used to determine the optimal disassembly plan.

Graphs represent diagrams that consist of nodes joined together by arrows [Berge, 1962; Wilson, 1979]. Consider a general disassembly problem that is represented by a graph, see figure 4.6. The good A has to be disassembled, so that the component M is recovered. The initial state of the good is $\underline{x}$ (1) while the state containing the desired component is called $\underline{x}$ (N+1). Obviously N decisions are needed to transfer $\underline{x}$ from the initial to the final state. The directed arrows {ab, ac, etc.} in the graph show the disassembly operations and the corresponding costs. We shall call the collection of decisions, one for each stage, which can achieve a transfer from the initial state (A) to the final state (M), a disassembly plan.

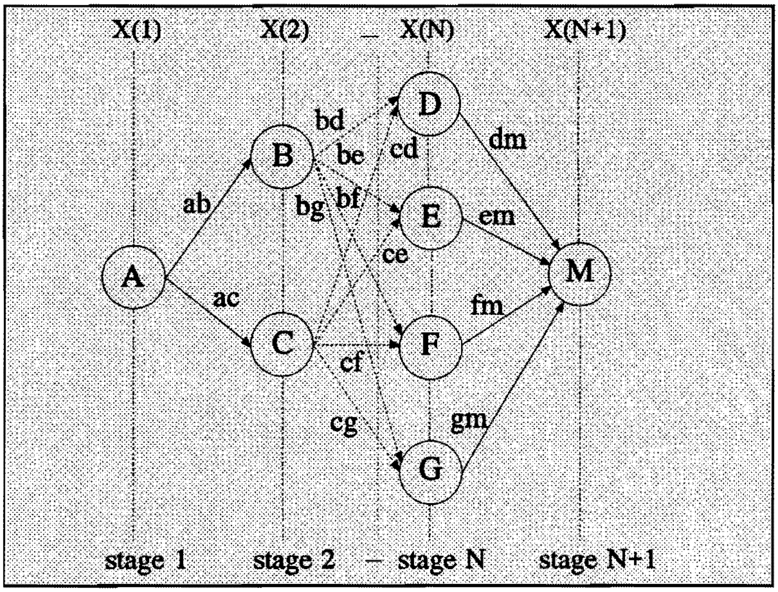



Figure 4.6: A disassembly process represented by a graph.

State $\underline{x}$ (k+1), which is reached during the disassembly process, depends upon the earlier state $\underline{x}$ (k), the foregoing decision $\underline{u}$ (k) and the number of passed stages k:

$$\underline{x}(k+1) = \Gamma_k\,(\,\underline{x}(k),\ \underline{u}(k)\,) \qquad k=1,2,\ldots,N \tag{4-11}$$

where Γ represents some mathematical operator.

From equation (4-1), a cost function can be derived:

$$J = \sum_{k=1}^{N} g_k\,(\,\underline{x}(k),\ \underline{u}(k)\,) \tag{4-12}$$

where g (k) is a cost function.
Then we require the minimization of $J$ by means of the choice of the optimum disassembly plan $\underline{u}^o(k)$, k = 1, 2, ... N. Theoretically it is possible to calculate every possible disassembly plan and then to choose the optimal decisions. However, for any real process this would quickly lead to an extremely large amount of computation. This can be simplified by using Bellman's Principle of Optimality, which allows one to solve the problem stage by stage. This principle states that: *"A policy is optimal if, at a stated period (stage), whatever the preceding decisions may have been, the decision still to be taken constitutes an optimal policy when the result of the previous decision is included"* [Bellman, 1962]. This is called the *principle of optimality* and expresses that an optimal policy only contains optimal subpolicies. However, it regards economic problems and should not be taken literally while solving design problems. This principle is the basis of a method for the optimization or mathematical representation of processes called *dynamic programming* [Beckmann, 1968]. It suggests that the best place to start the calculations is at $\underline{x}$ (N+1), i.e. the final state. The series $\underline{u}$ (N+1-k), ... $\underline{u}$(N) are calculated in order to arrive at $\underline{x}$ (N+1) from $\underline{x}$ (N+1-k) with the minimum costs. Beginning with k = 1, the values of $\underline{u}$ (k) giving the minimum cost are stored. The fact that not all possible $\underline{u}$ (k) need to be considered leads to a considerable reduction in computation. This can be formulated mathematically as follows. Suppose that $V_k$ {$\underline{x}$(N+1-k)} represents the costs incurred over k stages from the state $\underline{x}$ (N+1-k) to the final state $\underline{x}$ (N+1) by using some disassembly plan. Furthermore let $V_k^o$ be the minimum of $V_k$. Then the general recursive formula or algorithm of dynamic programming can be written as:

$$V_k^o\{\underline{x}(N+1-k)\} = \\ = \min_{\underline{u}(N+1-k)} [g_{N+1-k}\{\underline{x}(N+1-k)\}, \underline{u}(N+1-k)\} + V_{k-1}^o\{\underline{x}(N+2-k)\}] \tag{4-13}$$

This formula, starting with $\underline{x}(N+1)$, allows the optimal disassembly plan to be calculated. To illustrate the calculation, a simple example will be worked out, see Figure 4.7. In the figure, the costs associated with disassembly operations are given by means of arrows. We start with stage x(4) = D at the extreme right side and construct a table with two columns: one for all possible "routes" to x(3) and one for the corresponding costs, see Table 4.1.

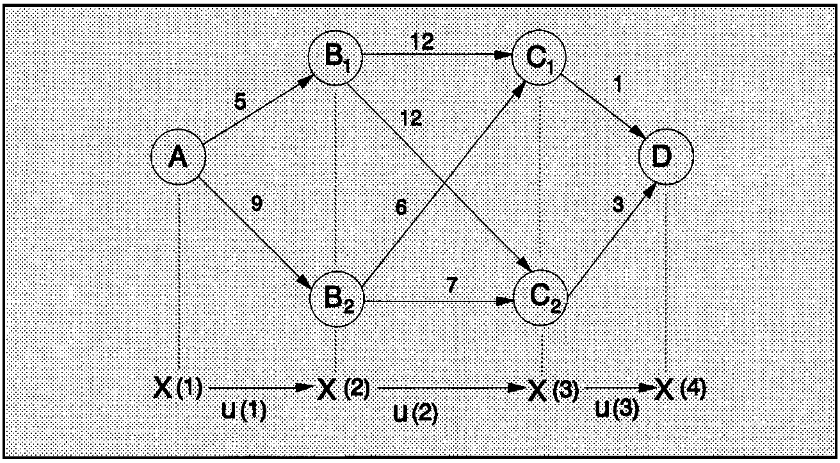



Figure 4.7: Example to illustrate the calculation of an optimal disassembly strategy.

Table 4.1: Costs to arrive at stage 3.

| Possible routes | Costs |
|---|---|
| U(3) | $V_1$ |
| $\{C_1, D\}$ | 1 |
| $\{C_2, D\}$ | 3 |

After comparing the possible routes, it can be seen that the route {C1, D} is the optimal decision ($V_1^o$) to arrive at stage 3. Now we go back one stage and check all possibilities to come from x(3) to x(2) together with the total costs made in the previous stage (3), see Table 4.2.

Table 4.2: Costs to arrive at stage 2.

| Possible routes | Costs |
|---|---|
| U(2) | $V_2$ |
| $\{B_1, C_1\}$ | 1 + 12 = 13 |
| $\{B_1, C_2\}$ | 3 + 12 = 15 |
| $\{B_2, C_1\}$ | 1 + 6 = **7** |
| $\{B_2, C_2\}$ | 3 + 7 = 10 |

For example, from B1 to D via C1 costs 13 units, whereas via C2 it would cost 15 units. This means that the total costs from D to B1 via C1 are 13, whereas via C2 are 15. It can be seen that the cheapest option is to go via C1. This means that if it turns out to go via B2, we should choose further to progress via C1 and not C2. This route represents the optimal decision $V_2^{o}$. We can apply the same tactic to decide how to arrive from x(2) to x(1). The calculated results can be found in Table 4.3:

Table 4.3: Costs to arrive at stage 1.

| Possible routes | Costs |
|---|---|
| U(1) | $V_3$ |
| $\{A, B_1\}$ | 1 + 12 + 5 = 18 |
| $\{A, B_2\}$ | 1 + 6 + 9 = **16** |

It is clear how one can find which decisions give the least total costs per stage. These correspond to the values assigned to $V_1^{o}$, $V_2^{o}$ and $V_3^{o}$. The other possible disassembly plans, in accordance with the Principle of Optimality, should not be considered. Clearly the result of the table is that the route **{A, B2, C1, D}** is the optimal disassembly plan, with a cost of 16 units.

In practice, one should be very flexible in order to select the correct disassembly process and to determine to what extent it should be executed. The price of spare parts, secondary materials, disposal costs, etc., are time dependent and change during a defined period. This makes the recovery issue extremely complicated. By using the suggested approach, the problems can be solved in a systematic way, which provides satisfactory results. This approach is the basis for a logical formulation, search and selection of the optimal disassembly process. It should be considered and used when dealing with issues in the field of disassembly.

## 4.5 Example: disassembling of a bearing unit

This section illustrates the applicability of the aforementioned approach for the determination of the disassembly strategy. For this purpose, a practical problem will be solved. It concerns the recovery of a roller's bearing unit. In fact, this is a simplified model of the roller presented in Figure 3.11 and described in Chapter 3. It is assumed that the company should take back and recover the rollers in the most feasible way. As was mentioned before, this case is used as an example only. It regards the recovery of the bearing unit after it has been removed from the tube.

It has been described how the product design can facilitate the development of a fully automated assembly system for bearing units. When dealing with disassembly, the most effective and economic procedure to reuse the bearing unit should be found. The simplified model of the bearing unit consists of the following details, see Figure 4.8:

- pos. 1 - axis
- pos. 2 - hub
- pos. 3 - bearing
- pos. 4 - rubber seal
- pos. 5 - cup

The axis and the bearing consist of metal fractions. The cup and the hub are made from plastic materials, while the seal is made from a rubber material. When the rollers are discarded, the bearing units are taken out of the pipe. Next, the bearing units are disassembled in order to regain the value added to them. As was suggested before, the disassembly strategy has to be established first. It begins with an extensive analysis of the discarded goods, which includes the determination of the number of poisonous and valuable elements (materials). In this case, there are no poisonous materials (components). Initially, the bearing can be considered a valuable component. However, it must be clear that the rollers have to be discarded because the bearing is exhausted. Its recovery is not feasible because the bearing does not have the required performance. Therefore, it is not a target for component reuse. The axis may also be considered a valuable part. This element can be used for all types of rollers. Its production is relatively expensive in comparison to the effort for recovery. Therefore the axis is the only target concerning the component reuse. This means that disassembly is required to extract the axis from the bearing unit.

After accomplishing the product analysis, the number of feasible disassembly plans have to be generated, using the graph method.

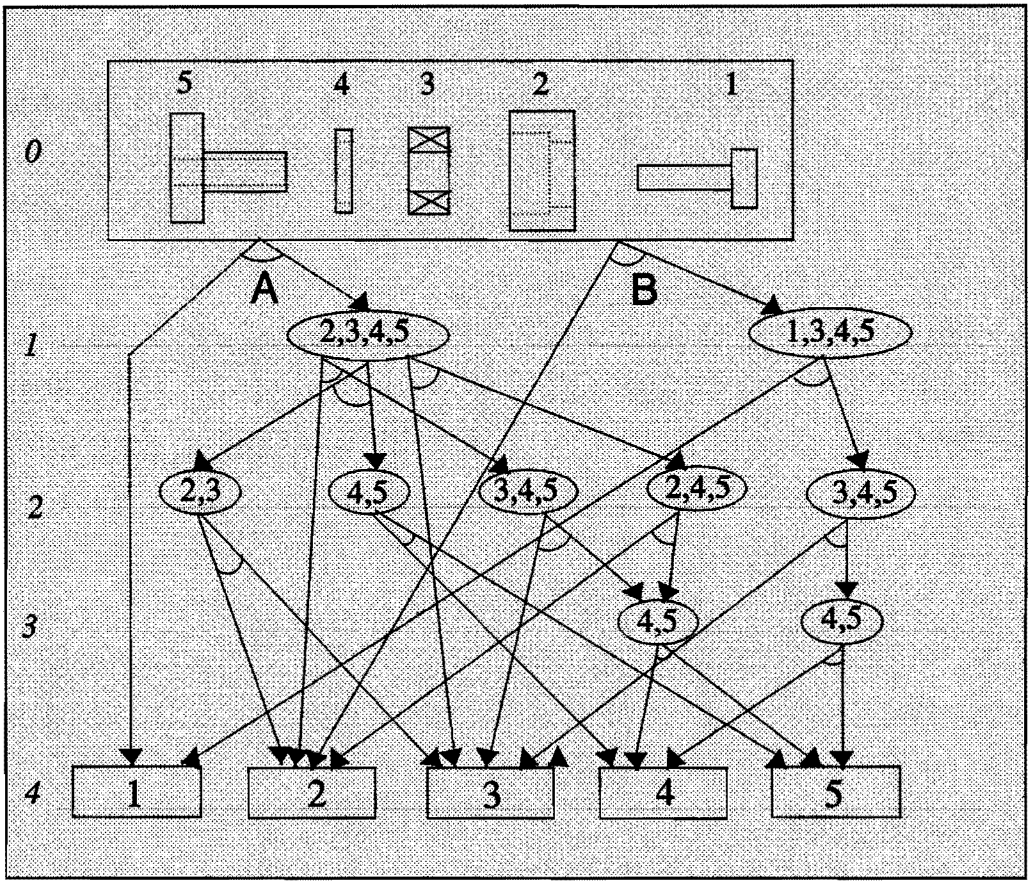



Figure 4.8: AND/OR disassembly graph of a bearing unit.

The AND/OR graph of the disassembly alternatives is given in Figure 4.8. There are two arcs (A, B) leaving the initial node. Each of these arcs correspond to one way the whole good can be disassembled. Similarly the other nodes in the graph have leaving arcs for each possible way in which their corresponding part can be removed, for more details see Appendix 4.1. The number of the feasible disassembly sequences shown in the figure is smaller than the theoretical one. This can be explained by the limitation caused by the absence of physical relations between the components and technical requirements. In this way, the number of disassembly alternatives and operations can be reduced considerably. Without this simplification, the search for the optimal disassembly plan would become extremely difficult and impossible for execution. For instance, consider a discarded good that consists of 20 components or fractions which should be disassembled. The theoretical number of disassembly alternatives in the corresponding AND/OR graph can be given by:

$$N = n! \tag{4-14}$$

where: N - theoretical number of alternatives;
n - number of components.

After substitution, this equation yields:

$$N = 20! = 2{,}43 \,.\, 10^{18} \;\; [alternative] \tag{4-15}$$

The search among this huge number of disassembly alternatives can not be accomplished within a reasonable amount of time even by a very fast computer. Consider a computer that is able to process $10^9$ operations per second. This means that the number of operations which can be processed per year is:

$$O = 10^9 \,.\, 3600 \,.\, 24 \,.\, 365 = 3{,}15 \,.\, 10^{16} \;[\; operation \;] \tag{4-16}$$

Then the amount of time required to process all disassembly alternatives can be given by:

$$T = \frac{N}{O} \;[\; year \;] \tag{4-17}$$

The substitution of (4-15) and (4-16) in (4-17), gives us the following amount of time:

$$T = \frac{2{,}43 \,.\, 10^{18}}{3{,}15 \,.\, 10^{16}} = 77 \;[\; year \;] \tag{4-18}$$

This example shows that it is impossible to consider the theoretical number of disassembly sequences. Moreover, it is necessary to reduce the number of disassembly alternatives and to investigate the feasible alternatives only.

Concerning the rollers, two disassembly plans are possible from a technical viewpoint. The first one starts with the disassembly of the axis, and the second with the disassembly of the hub. According to the theory, both disassembly plans should be investigated to determine which of them is more economical. However, in practice some considerations can be made that reduce the number of plans and simplify the optimization process. In this context, it can be roughly estimated that the disassembly of the hub does not reduce the costs to obtain the axis. This is logical as these elements do not have any physical connections. In addition, the hub is not a valuable component and its disassembly, if necessary, should be carried out after accomplishing the desirable operations in order to obtain the axis. In other words, the axis should be disassembled first, which means that the second disassembly plan (B) can be rejected. Based on the above, the disassembly plan (A) is selected for execution; it is represented by a dotted line in Figure 4.8. The choice how to proceed further must be based on the economic considerations as formulated in the previous section. This choice concerns how to regain the money value added to the other components (N=2, 3, 4, 5) with minimum costs. This means that at every stage one should decide whether to proceed with disassembly or to send the fractions to the shredder. For this purpose the revenues and costs of disassembly, dismantling and recycling are compared to define which process is the most profitable. Table 4.4 contains the data necessary to calculate the costs of the various recovery options. The numerical values are fictitious and are used to show the applicability of the suggested method only.

Table 4.4: Disassembly chart of a bearing unit.

| N | Name | Material | Material price [money units/mass units] | Price obtained by selling the compon. [money units] | Weight [mass units] | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{sep}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Axis | Steel | 1.20 | 1.70 | 0.14 | 0.21 | 0.10 | 0.11 | 0.04 |
| 2 | Hub | Plastic | 0.90 | 0.18 | 0.13 | 0.36 | 0.10 | 0.04 | |
| 3 | Bearing | Steel | 1.20 | 0.04 | 0.15 | 0.38 | 0.10 | 0.11 | |
| 4 | Seal | Rubber | 0.80 | 0.06 | 0.08 | 0.25 | 0.14 | 0.04 | |
| 5 | Cup | Plastic | 0.90 | 0.08 | 0.11 | 0.29 | 0.14 | 0.04 | |

We start with the determination of the recovery option that is the most profitable for the reuse of the bearing. Generally, the bearings are exhausted and can only be reused as secondary material. By substituting the costs and revenues in equation (4-7), the following results are obtained:

$P_{dis,\,fe}$ = 0.15 . 1.20 - 0.38 = - 0.20 [money units]
$P_{dm,\,fe}$ = 0.15 . 1.20 - 0.10 = 0.08 [money units]
$P_{shr,\,fe}$ = 0.15 . 1.20 - 0.11 - 0.04 = 0.03 [money units]

In other words:

$P_{max,\,fe} = P_{dm,\,fe} = 0.08$ [money units]

This means that the extraction of the bearing by means of dismantling generates a pure ferrous fraction and the highest revenues. Proceeding with dismantling means that the search for the optimal plan should be continued until the component is removed. The cheapest way to accomplish this task is at level 2, where the bearing is removed by means of a special press; this step implies a dismantling operation.

After the most feasible recovery options to remove these parts are determined, we have to determine how to proceed further with the other components (N=2, 4, 5). In general, after the removal of the bearing by means of dismantling, these components are not fixed any more. However, they are not completely separated to be suitable for reuse yet. It is supposed that after the dismantling they may be clamped together so that further separation is required. By utilizing the suggested approach, the cheapest option for their recovery can be determined. The following equations are valid for the recovery of the plastic hub:

$P_{dis,\,pl}$ = 0.90 . 0.13 - 0.36 = - 0.24 [money units]
$P_{dm,\,pl}$ = 0.90 . 0.13 - 0.10 = 0.02 [money units]
$P_{shr,\,pl}$ = 0.90 . 0.13 - 0.04 - 0.04 = 0.04 [money units]

This means that the maximum profit is:

$P_{max,\,pl} = P_{shr,\,pl} = 0.04$ [money units]

In addition, it can be found that this profit is higher than the profit which can be obtained if the hub is disassembled and then recovered as a component. This is given by:

$P_{dis',\,pl} = 0.18 - 0.36 = -\,0.18$ [money units]

In the same way, the profits of the rubber seal and the plastic cup can be determined. Then by using the dynamic programming, a backward search is executed to find the optimal disassembly plan. It is found that after the axis is disassembled and the bearing is removed by means of dismantling the shredding option is the most feasible from an economic viewpoint. In other words, at this stage the disassembly (dismantling) operations should be terminated and the remaining fractions (N=2,4,5) should be sent to a shredder for material recycling. After shredding, the materials are separated by using a feasible and well-known technique. It is based on the different elasticity properties of these two materials [Ansems, 1989]. With this phase the total disassembly process can be accomplished and the disassembly strategy can be established. It is represented in Figure 4.9 and consists of the following steps:

1) Disassembling of the axis.
2) Dismantling of the bearing.
3) Shredding of the plastic and rubber.
4) Separation of plastic and rubber.

To calculate the money value which can be obtained from the recovery of the bearing unit, besides the costs for the above mentioned operations, the miscellaneous costs should be taken into account. They include transport, logistics, energy and maintenance costs.

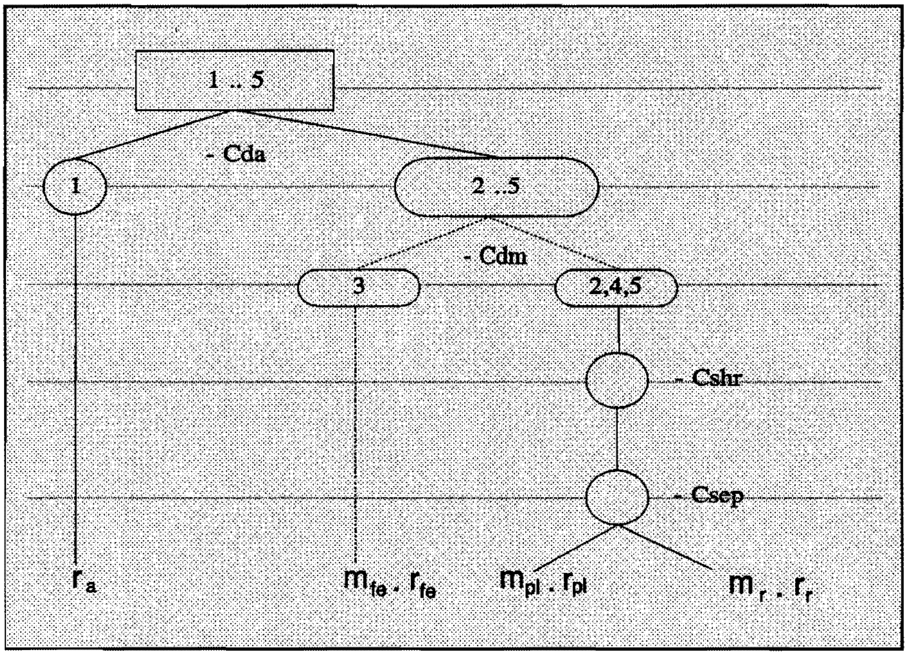



Figure 4.9: Disassembly plan of a bearing unit.

Thus, the maximum money value that can be obtained from disassembling the bearing unit is given by the following equation:

$$P_{\max} = r_a + m_{fe}.r_{fe} + m_{pl}.r_{pl} + m_r.r_r - C_{dis} - C_{dm} - C_{shr} - C_{sep} - C_m \qquad (4\text{-}19)$$

where:

| | | | |
|---|---|---|---|
| | $P_{max}$ | = | maximum recovered value of the good |
| | $r_a$ | = | revenues from the axis |
| | $m_{fe}$ | = | mass of the ferrous fraction |
| | $r_{fe}$ | = | revenues from the ferrous fraction per mass unit |
| | $m_{pl}$ | = | mass of the plastic fraction |
| | $r_{pl}$ | = | revenues of the plastic fraction per mass unit |
| | $m_r$ | = | mass of the rubber fraction |
| | $r_r$ | = | revenues from the rubber fraction per mass unit |
| | $C_{da}$ | = | disassembly costs |
| | $C_{dm}$ | = | dismantling costs |
| | $C_{shr}$ | = | shredding costs |
| | $C_{sep}$ | = | separation costs |
| | $C_m$ | = | miscellaneous costs |

The substitution of the numerical values from Table 4.4 in this equation yields:

$$P_{\max} = 1.70 + 0.15 \,.\, 1.20 + 0.24 \,.\, 0.90 + 0.08 \,.\, 0.80 - 0.21 - 0.10 - \\ - 0.04 - 0.04 - 0.03 \approx 1.74 \; [\textit{money units}]$$

Based on this result, we can judge whether the obtained profit satisfies the expectations and requirements. In this way, a decision can be taken whether recovery of the bearing units is economically valuable enough for the firm or can be neglected. It should be clear that the determination of the disassembly strategy and profit depends upon a number of aspects, such as market price for secondary materials, labour costs, machine costs, logistical costs, available customers and legislation rules. This means that if any of these parameters is changed, the disassembly strategy should be changed as well. In other words, the disassembly strategy should be determined for every particular product and actualized when there is a change of the input parameters.

This example clarifies how the disassembly strategy should be determined and carried out. It shows the potency of the proposed approach and its application in solving a practical problem. After this stage has been accomplished, it is followed by the development of the corresponding disassembly system, which should be able to carry out all required operations.

## 4.6 Conclusions

Various factors influence and make the disassembly process complicated and difficult for execution. Their impact on the development of a feasible and profitable process and system can be observed in different stages of the entire design process. However, there is no sense in approaching the disassembly dilemma without establishing a clear plan for problem solving. In this context, the accurate determination of the disassembly strategy is of significant importance when one is dealing with disassembly and recovery problems. In fact, the disassembly strategy is the core of the entire development process concerning the design of disassembly systems. In this context, some methods for the generation of the disassembly sequences have been developed, which only cover a limited part of the entire disassembly strategy. These methods are based on the execution of the disassembly operations as reverse assembly sequences. This means that all components will be removed from the assembly, which is not necessary if one considers the disassembly process as a means to recover the discarded goods. In addition, there are no economic considerations involved in these methods with regard to the recovery of the discarded goods in the most profitable way. From the presented methods for the generation of the disassembly sequences, it has been found that the AND/OR graph method is the most suitable one concerning the disassembly issue. This method gives all feasible disassembly sequences and the possibility to use the power of dynamic programming to find the optimal disassembly plan. In this way, the search process can be based on technical and economic requirements while fulfilling the legislation demands, including environmental aspects. While using this method, we have to create a general method that provides us with the disassembly strategy and is applicable to any particular case. Such a technique should involve a procedure about the determination and execution of the following items:

- Generating the number of feasible disassembly plans (operations).
- Determination of the recovery profit per disassembly step.
- Determination and application of the most feasible disassembly plan (process).

The aim is to establish criteria that would allow one to make the accurate choice among the numbers of disassembly levels and to ensure the desired output. To achieve satisfactory results, a new approach for the determination of the optimum disassembly strategy has been suggested. It involves a graph method for the generation of the feasible disassembly plans and a mathematical tool, and the method of dynamic programming to define the most optimal disassembly level and process. Using this comprehensive approach, the most feasible disassembly strategy can be created, which is an indispensable condition to proceed with the design of the corresponding disassembly system. Besides the determination of the disassembly strategy, which is a significant part of the entire development process, other design issues should be considered as well in order to develop the most feasible disassembly system. These issues should be involved in a systematic approach so that the most feasible system can be designed. In this context, the following chapter suggests a systematic approach, which can be used when solving recovery issues and designing disassembly systems.

# Chapter 5

# A systematic approach for the development of disassembly systems

## 5.1 Introduction

The development of sustainable production has become a priority of our entire modern society. The main issue of this new concept is to use natural resources in a conscious way and to preserve the globe for the next generations. In this context, the design and implementation of disassembly systems has been recognized as a weapon to attack the huge flow of discarded goods, now and in the future. Only by disassembly, the discarded goods can be reused in an environmentally sound way while a desirable profit is generated. There is no doubt that disassembly systems need to be introduced in practice in order to give a comprehensive answer concerning the way to process the current discarded goods and how to design new sustainable products. For this purpose, a systematic approach is needed that describes a methodical way to tackle and solve disassembly issues.

The absence of knowledge and experience in the field of disassembly makes the design of disassembly systems very uncertain. To prevent most of the occurring problems and to encourage firms to consider disassembly, a lot of work needs to be done in the near future. In this context, a comprehensive systematic approach for the development of disassembly systems is required to reduce the level of indecision during the entire design process. The systematic development of such an approach is based on a fundamental science and engineering design, as was suggested in Chapter 3. The main segments of engineering design have already been reviewed and discussed in the previous chapters. Their links to disassembly have been highlighted. The aim is to use the available knowledge and experience that may be applicable to disassembly in the most competent way. For this purpose the fourth segment of engineering design science, being the theory of special processes and systems, will be extended with disassembly issues. This will broaden the external properties: design science and experience, and contribute to future developments in this field.

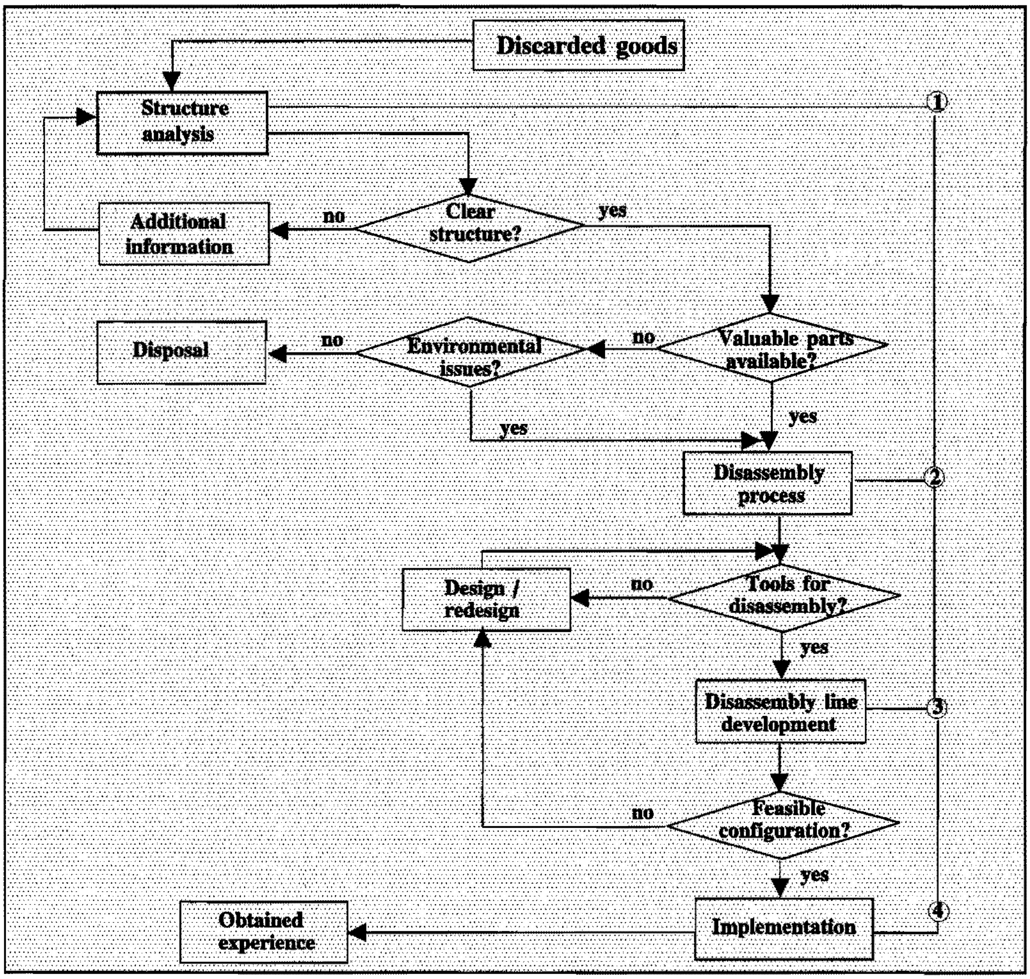



Figure 5.1: A general disassembly approach.

Without having a clear plan in the beginning of the design process, there is no sense in proceeding any further with the development of disassembly systems. In this regard, a four-step general disassembly approach is suggested to compensate uncertainty, see Figure 5.1. It should be considered before deciding whether to start with the disassembly of discarded goods. Its aim is to be able to design a recycling process and system that is effective and efficient. The first step is the most important, since a strategy for further recycling and disassembling is established. Within this step, the structure of the discarded goods is analyzed and the value of components and materials is determined. This means that the disposal taxes are compared with the cost for recycling, which results in a final decision concerning proceeding with the next step. This decision should be taken on the basis of a number of criteria like: technical, economic, ergonomical, environmental and social considerations. Concerning the disassembly of discarded goods, these criteria can be reduced to two main issues: economic profit and environmental benefit. They comprise the criteria mentioned above and at most represent the reason to attempt disassembly. Therefore, if the main goals: economic profit and environmental benefit are not fulfilled, the process ends with the disposal of the discarded goods. These significant disassembly issues are involved in a disassembly strategy, which should be established at this step, as was described in detail in Chapter 4. After accomplishing the first step, it should be clear whether proceeding with disassembly is feasible. If the result is not positive, the process ends with the disposal of the discarded goods. Otherwise, the development of the disassembly process and system should be continued (step 2 and 3). The design process should be executed in a structured and methodological way, as will be described in the following sections. The most feasible disassembly system should be chosen on the basis of various criteria as was explained already. After evaluation of the number of competitive alternatives, the implementation follows of the selected disassembly systems in practice (step 4) .

Before starting with the systematic development of disassembly systems, it is necessary to create a distinct product life cycle model including the recovery issue. The aim is to present the disassembly systems as a segment that closes the loop of the entire product life cycle. In this way, the systems' boundary and all important restrictions and requirements towards the implementation of such systems can be determined. This should provide a clear picture concerning the systems' relationships and interactions with the other elements of this complete life cycle model as will be described in Section 5.2. This information will help individuals and industrial firms to consider all important aspects that are of influence on the quality of the developed disassembly processes and systems.

## 5.2 A complete product life cycle model

All goods follow a common chronological sequence during their existence, often referred to as the product life cycle. The introduction of disassembly systems aims "closing the loop" of a product at different stages of its life cycle. The necessity to design such systems arises because of the new requirements being made toward the reuse of discarded goods and protection of the environment.

Before any attempt is made to develop a disassembly system, it is necessary to consider all the aspects that influence this process. Typically, development of new goods starts on the basis of a set of specifications based on the assessment of the market needs. However, the useful life does not end when a product is sold, but rather when it is recycled and disposed of. This viewpoint changes the ordinary concept about the product life cycle. It highlights the need for design of disassembly (recovery) systems. In this context, the product life cycle is considered to be a loop, which to some reasonable extent never ends. Besides the well known segments of this chain, such as market, design & development, production, distribution, usage, maintenance & repair, the new activities associated with the recovery and reuse of discarded goods should be considered. This involves the collection of discarded goods, creation of a secondary market, service, disassembly, dismantling, recycling and disposal. All these aspects should be represented in a disassembly model in order to make the entire disassembly process easy to understand. Therefore, the development of a comprehensive disassembly model is the first step in the suggested systematic approach. It includes the gathering of the required information about the entire product life cycle. Based on these data, the corresponding system should be designed while accommodating the demands made by the goods to be recycled.

The model, which is given in Figure 5.2, depicts a new approach and represents a general life cycle model that includes the recovery of discarded goods. It can be seen that the life cycle begins with a market need. As was emphasized before, the green image of the goods is a very important issue nowadays. This is the reason that it should be part of the early stage of product development. With this new approach, the discarded goods will be processed in such a way that they will be reused to some extent for various purposes. It is possible to sell the goods to a secondary market or to recover them on different levels. Our vision is that recovery should begin after collection of discarded goods. As was mentioned in Chapter 4, the assumed disassembly (recovery) process, consists of the following main steps:

- Service.
- Disassembly.
- Dismantling.
- Recycling.
- Disposal.

Every step has a different purpose and shows different levels from the entire recovery process. The intention is firstly to extend the entire life cycle of the goods and secondly to reuse every valuable component or material. What system should be exactly developed depends upon many factors. The main one is what kind of discarded goods it has to deal with. One can imagine that a good with durable components, which is at the beginning of its life cycle, will require a service or disassembly system. By contrast, a dismantling or

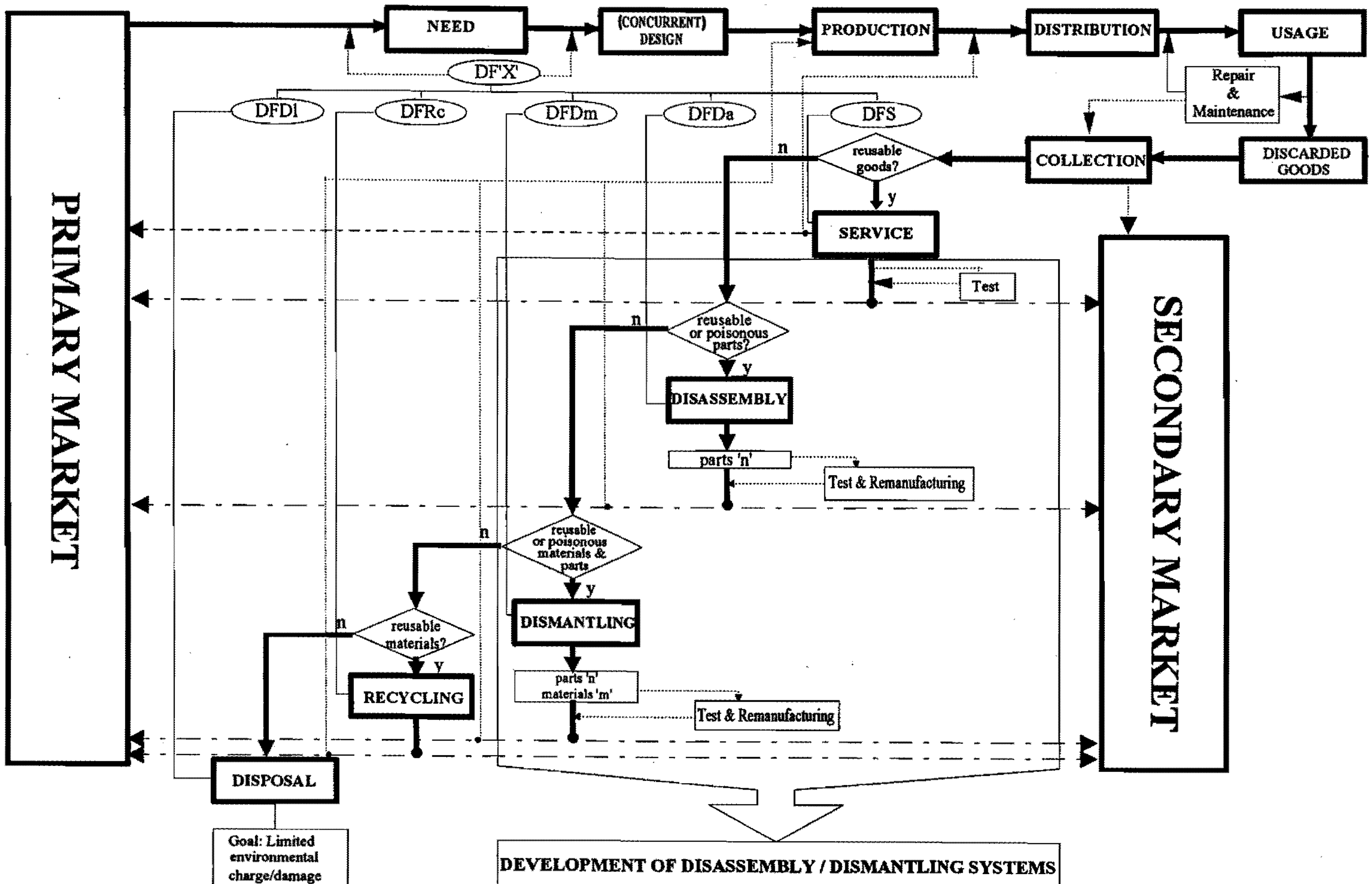



Figure 5.2: A general life cycle model.

recycling system should be introduced for the reuse of materials. The combination of these sub-systems into an entire disassembly (recycling) system is also evident. The decision what kind of system should be developed can be taken after a clarification of what kind of discarded goods are going to be processed, what the legislation rules are, what the policy of the firm is, etc. After every step has been executed, the valuable goods, parts or materials should be sold to the main or secondary market, or possibly involved in the current firm's production (assembly) process. The choice how to proceed with the recovered goods can be taken after the execution of a proper test. The issue is to determine the new properties of the goods exactly as well as their quality and expected new life cycle. If satisfactory results are found the goods should be remanufactured if it is profitable. This means that all disassembled parts and units should be extensively inspected. Further, they are repaired and approved for reuse. The issue is to recover a discarded good so that its new properties are compatible with those for newly produced products. The experience that is obtained from these activities should be used as input for the development of new design methods. These methods are regarded as new aspects and supplement a complete design approach being made for the development of "green" products. This approach includes the following new issues:

- Design for easy Distribution.
- Design for easy Service.
- Design for easy Disassembly.
- Design for easy Dismantling.
- Design for easy Recycling.
- Design for easy Disposal.

The aim is to involve the aspects of reuse in the early stage of product design. This would contribute significantly to successful recycling and reusing of goods and materials in the near future.

As can be seen, the purpose of disassembly systems is not just to solve the current problems concerning the huge flow of discarded goods. Besides that, the result of their implementation will be conscious design, production and reuse of sustainable goods. Many disassembly systems should be introduced in practice during the course of time as they are the most efficient. To facilitate the design and implementation of disassembly systems a systematic approach is offered that covers all issues associated with the reuse of discarded goods and materials. The emphasis lies on the systematic design of disassembly systems from an industrial engineering viewpoint.

## 5.3 Systematic design of disassembly systems

Various attempts have been made to describe the design process and to prescribe a general approach for tackling design tasks [Kroonenberg, 1975; Pahl, 1984; VDI, 1990; Roozenburg, 1991; van Bragt, 1993]. Every approach to design has its own properties and comprises diverse problems. Generally, the design process is broken down into a number of main stages. Within these stages numerous design methods are introduced to accomplish a defined design task [Cross, 1994]. Some methods are general and can be used at any level of resolution and others are more specific and are only applicable to a particular step or stage. What design method should be used depends on a number of factors like:

- Who is attempting the design process?
- What branch?
- What is the complexity of design?
- etc.

However, every design approach strongly depends upon the designer's strategy and his own view about how to tackle the problems. Moreover, design is a creative process and every new issue brings innovative aspects that should be approached in a particular manner. The main design stages and tools that have already proved their worth should be adapted and applied to solve these new issues. In this context, two main questions should be considered during the execution of a design:

1) How should the design process be structured?
2) What methods should be used in every design stage?

The suggested systematic approach for the design of disassembly systems aims to establish a general procedure for the execution of the entire design process. For this purpose, the issues of engineering design are regarded from a disassembly viewpoint. The approach is not intended to replace creativity, intuition or experience but to support the designer, thus ensuring that all relevant issues will be considered and successfully solved. It is proposed to structure the design process as given by Pahl (1984) because this makes the process transparent and easy to understand. The most obvious advantage is that during the conceptual design, the process is broken down into a number of steps for which suitable solutions should be found. This facilitates the designer's task who has to find the optimal technical solutions. However, for the purpose of this research, the design process includes two more phases, which involves new issues associated with the design of disassembly systems. In this context, the design process is structured into the following main phases:

1) Collection of market information.
2) Clarification of the task.
3) Conceptual design.
4) Embodiment design.

5) Detail design.
6) Implementation.

The first three stages are the most important as in these phases the strategic decisions should be taken. Even a brilliant embodiment or detail design can not compensate a bad formulation of the problem or a worthless concept. This is the reason that most of the effort and attention should be devoted to the first three stages. In addition, the various design stages have to be executed concurrently in order to identify and solve problems before it is too late.

The systematic approach to the design of disassembly systems starts with a comprehensive collection of **market information.** The aim is to achieve the company goal, to generate profit and to gain advantages in the market, see Figure 5.3. This is an iterative process, which implies that not only the market can determine a need and/or influence a decision. It is more important to search for a need, recognize it and to take a decision on how to generate profit out of it. This is the main issue when regarding the reuse of discarded goods and materials. As many companies still do not recognize the need for recycling of their goods, the ones that are approaching the problem will have an advantage and will be more competitive in the near future. At the current stage, one of the most important factors that stimulates disassembly and recovery is the body of legislation rules. They should be carefully studied in order to determine what goods may be attractive for recycling and reuse. This implies that the legislation in the industrialized countries is becoming more stringent. This means the introduction of high disposal costs and imposes considerations that help close the loop of the product life cycle. From a governmental viewpoint, the new rules are meant to protect the environment. However, companies are primarily interested in generating profit. It should be clear that these main issues of recycling are not in contradiction, but that they complement each other. Based on the legislation rules, a strategy can be established concerning which discarded goods are to be the subject of further investigation. It would be wrong to start disassembling and recycling goods that do not have a direct impact on the environment and have a limited added value. The aim is to disassemble and reuse goods for which a fee for their treatment can be obtained and potential customers exist for the recovered components and materials.

The market price of the raw materials compared with the price of the secondary materials is also an important aspect. When approaching disassembly and recycling, a firm should estimate whether the price of the secondary materials is attractive in comparison to the primary materials and what benefit can be expected from recovery. Of course, there are a lot of market price deviations but a rough appraisal is required in this phase.

The organizational disassembly structure as a whole and that of the company determines whether the plant is able to carry out the entire disassembly process alone or whether any additional support is required. If so, then an assessment should be made as to what possibilities there are to create a reliable organizational structure. The absence of such a formation may postpone disassembly, because it may not be feasible in that structure.

The present technologies are playing a crucial role in recycling. There is no sense in attempting the recycling of goods if there are no proper technologies to accomplish the entire process. Therefore the goods and the corresponding process should be considered concurrently along with the available technologies. The possibilities for the development of the necessary technologies in due time should also be deliberated.

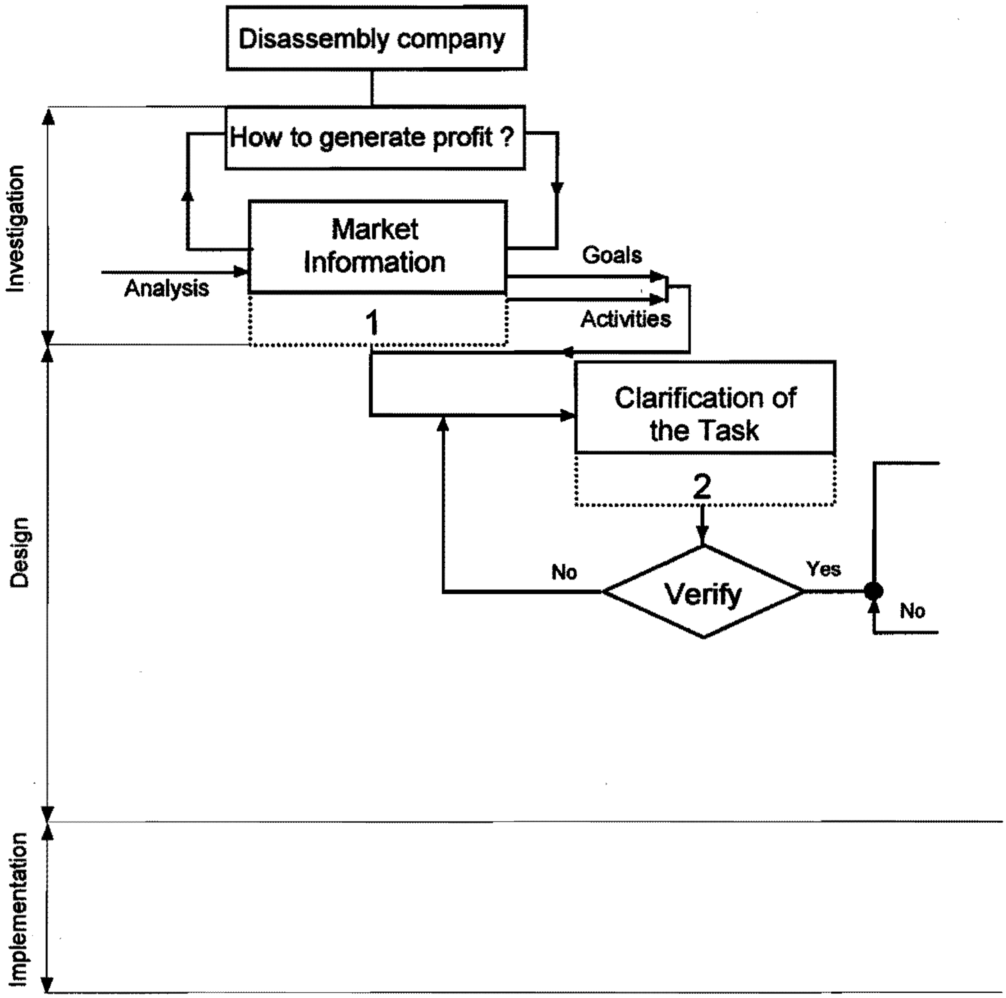
The logistic support during the reuse of discarded goods and materials is also significant. It covers aspects like supply of discarded goods, potential customers, transport, etc. In other words, the input and output streams should be controlled in such a way that profit is generated. In this context, the source and destination of every production stream has to be defined. Only responsible logistic support can guarantee a reliable and profitable disassembly process.

Comprehensive information should be provided about the discarded goods, their characteristics and the expected economic profit and environmental impact from disassembly. The aim is to determine the product's structure and to define the poisonous and valuable components; what the prices are assigned to them and who the potential consumer is. In addition, the current and the expected disposal costs imposed by the legislation must be deliberated. They can change the disassembly strategy considerably as disposal costs are gradually rising, so more efforts are expected to reduce the amount of waste.

All these aspects, which belong to the market investigation phase, complement each other. The aim is to determine the most attractive subject for further research. To obtain reliable data, the method of QFD can be used. The expectation of customers about the prices of secondary products, the penalty costs for disposal, the quality requirements, etc., should be listed against the design characteristics of a disassembly system that is able to fulfil these requirements. In this manner, in the early stage of design, a rough estimation can be made of the most feasible disassembly system. This would guarantee that no important market requirement is omitted, which is significant for the effective execution of the entire design process.

**Clarification of the task** implies that the design goal must be identified as fully and clearly as possible. In addition, the constraints should be specified in order to define the boundary for the goal. This phase begins with an exhaustive analysis of the goods' dynamic variables:

- Assortment.
- Structure.
- Components.



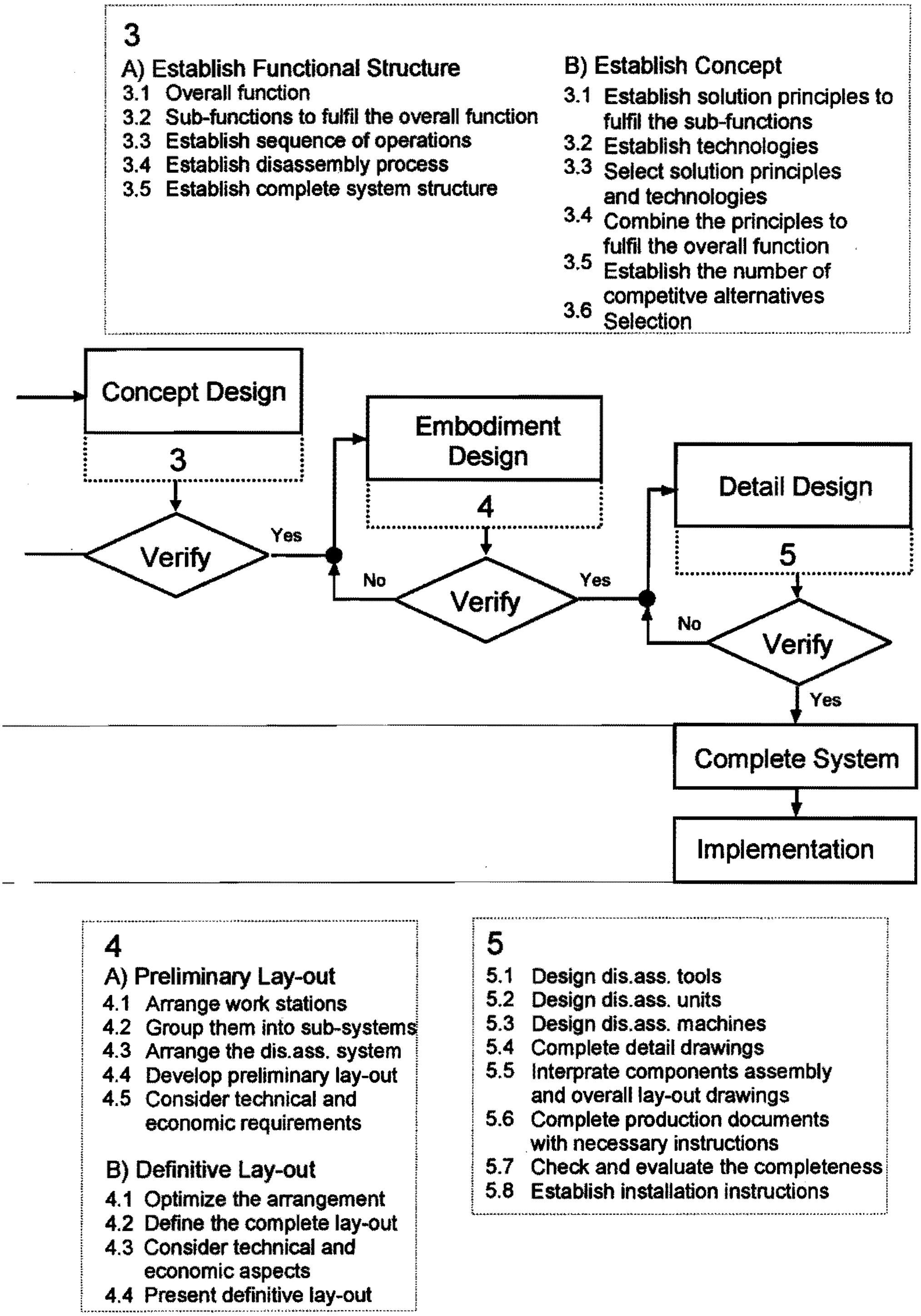

**1**

- 1.1 Legislation rules
- 1.2 Selection of products
- 1.3 Market price
- 1.4 Organizational structure
- 1.5 Technologies
- 1.6 Logistics
- 1.7 Information
- 1.8 Disposal costs

**2**

- 2.1 Product assortment
- 2.2 Product structure
- 2.3 Product components
- 2.4 Establishing requirements
- 2.5 Disassembly strategy (planning)
- 2.6 Possibilities for realization
- 2.7 Plan organization for problem solving
- 2.8 Determination of significant system parameters

Figure 5.3: The systematic approach.


3
A) Establish Functional Structure
3.1 Overall function
3.2 Sub-functions to fulfil the overall function
3.3 Establish sequence of operations
3.4 Establish disassembly process
3.5 Establish complete system structure
B) Establish Concept
3.1 Establish solution principles to fulfil the sub-functions
3.2 Establish technologies
3.3 Select solution principles and technologies
3.4 Combine the principles to fulfil the overall function
3.5 Establish the number of competitve alternatives
3.6 Selection
Concept Design
3
Verify
Yes
Embodiment Design
4
No
Verify
Yes
Detail Design
5
No
Verify
Yes
Complete System
Implementation
4
A) Preliminary Lay-out
4.1 Arrange work stations
4.2 Group them into sub-systems
4.3 Arrange the dis.ass. system
4.4 Develop preliminary lay-out
4.5 Consider technical and economic requirements
B) Definitive Lay-out
4.1 Optimize the arrangement
4.2 Define the complete lay-out
4.3 Consider technical and economic aspects
4.4 Present definitive lay-out
5
5.1 Design dis.ass. tools
5.2 Design dis.ass. units
5.3 Design dis.ass. machines
5.4 Complete detail drawings
5.5 Interprate components assembly and overall lay-out drawings
5.6 Complete production documents with necessary instructions
5.7 Check and evaluate the completeness
5.8 Establish installation instructions

These three items have already been determined as dynamic variables that influence the design of assembly systems. The same holds for disassembly, so they should be considered in detail. At the current stage of disassembly, it is very difficult to provide reliable information concerning the discarded goods. Although some data about the structure of the goods and their components can be obtained from old drawings, it can not provide comprehensive and reliable information. This is because many components have been replaced by maintenance or repair work during the useful product life cycle. What the new components are and what their quality and price is, is unclear. This lack of information must be compensated to some extent. This is achieved by recovering the good's structure by the creation of new drawings, pictures, etc. Not all details have to be retrieved, only those that are significant for disassembly. After a number of discarded goods are investigated, the actual structure can be established. It will give a lot of deviations from the original structure. These deviations should be examined and their influence on disassembly should be determined. To accomplish of this task, it is recommended that a method be introduced which is similar to Failure Mode and Effects Analysis (FMEA) [Ford, 1988]. It is called User Mode and Effects Analysis (UMEA) and aims to provide information about changes that have been made in the good's structure during the useful product life, see Appendix 5.1. In addition, the consequences of these modifications concerning the quality, price, disassembly strategy, required disassembly tools, etc. can be determined. With the help of UMEA, disassembly requirements can be established with respect to various kinds of discarded goods.

The core of the clarification of the task is to determine the disassembly strategy. As was described in Chapter 4, it gives the optimal disassembly process, which contains the required steps for accomplishing the established goals. Based on the analysis of the good, a number of compulsory and desirable disassembly operations are defined. The obligatory operations imply environmental aspects while preferable ones imply the generation of a certain economic profit. The precise establishment of the disassembly sequences and determination of the disassembly level has been described in detail in Chapter 4. The proposed method should be used when defining a disassembly strategy. In addition, one has to consider whether the generated disassembly operations can be realized with the present technologies, machines and tools. For this purpose, the analysis of the goods, and the development of the process and corresponding disassembly system should be considered simultaneously. In addition, the system's cycle time should be determined according to the annual production rate, thus imposing requirements on the number of work positions and the system's lay-out. After accomplishing this phase, the results should be evaluated and verified. If they satisfy the expectations, the following design step can be carried out. In addition, some important system parameters should be determined, like the economical life cycle of a product, required annual production rate, required diversity per product type, required volume of a batch and frequency of changing the technologies used

[Sanders, 1995]. Based on the aforementioned, the cycle time of the system should be found before developing the system concept, as it gives some limitations that can not be neglected. The minimum cycle time required to fulfil the annual production rate can be found by the following equation:

$$t = \frac{D \, . \, k_{sh} \, . \, \delta \, . \, k_h \, . \, 3600}{P_a} \text{ [sec]} \qquad \textbf{(5-1)}$$

where:

| | | | |
|---|---|---|---|
| where: | $t$ | = | required cycle time |
| | $D$ | = | working days per year |
| | $k_{sh}$ | = | number of shifts |
| | $\delta$ | = | system availability |
| | $k_h$ | = | working hours per day |
| | $P_a$ | = | annual production rate |

The essence of a general **conceptual design phase** has been described in Chapter 3 concerning the design of an assembly system. The same considerations and steps can be used for the design of a disassembly system concept. For the sake of clarity, this stage is divided into the following sub-phases:

1) List the number of functions that are essential for the disassembly process.
2) For each function, list the technical means by which it can be executed.
3) Create a morphological chart containing all possible sub-solutions.
4) Identify and choose those combinations of sub-functions which fulfil the overall function without going beyond the constraints of the criteria.
5) Evaluate and select the most feasible disassembly system.

First, the overall function structure should be established and broken down into a set of essential sub-functions. They must fulfil the requirements concerning the discarded goods defined. In other words, the number of sub-functions should correspond to the number of disassembly operations according to the disassembly strategy. To execute the disassembly process, a number of suitable means should be found that fulfil the corresponding sub-functions. In addition, a block diagram should be drawn that clearly represents the complete structure. The purpose of this approach is to allow:

- Clear definition of existing sub-functions.
- Determination of sub-functions that will facilitate the subsequent search for solutions.
- Combination of these sub-functions into a simple and clear function structure.

Then we have the search for solution principles to fulfil the sub-functions. The number of sub-functions can be listed together with the possible solutions or technical means in a matrix table, see Figure 5.4. For instance, in the columns we list the number of solutions of any disassembly process and in the rows the corresponding technical means. Having a clear description of the disassembly process and the technical means, which fulfil these functions in a matrix, one can create the number of system configurations. This is achieved by combining solution principles to fulfil the overall function. The arrows in Figure 5.4 show the process of combining solutions into a set of systems configurations. In this example, two compatible variants are selected:

a) Variant 1: $S_{11} + S_{22} + ... + S_{ji} ... + S_{n2}$;

b) Variant 2: $S_{12} + S_{21} + ... + S_{jm} ... + S_{ni}$.

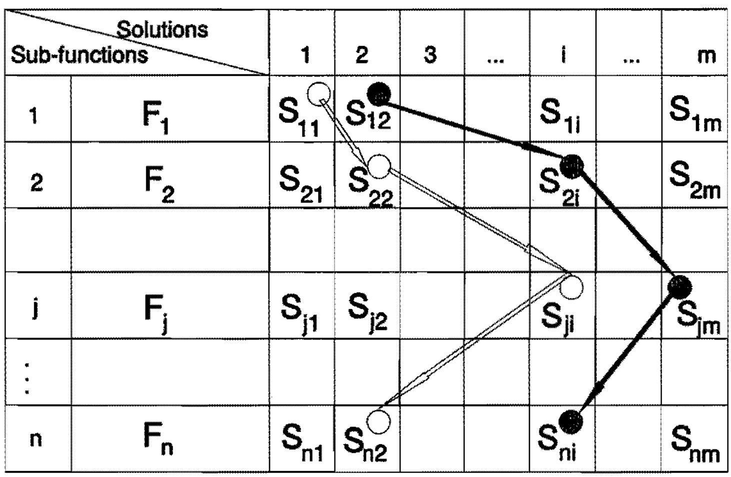



Figure 5.4: A matrix chart and combination of solutions.

The last step in this stage is the evaluation and selection of the most suitable disassembly system. This is achieved by a set of criteria and evaluation of every variant against the others. The suggested procedure is called the method of the *morphological analysis* [Kroonenberg, 1975; Cross, 1994]. This method encourages the designer to identify new combinations of elements and offers the opportunity for systematic investigation and development. It includes the considerations of all important aspects while every meaningful step is taken.

During the **embodiment design phase** the designer should determine and represent a definitive lay-out of the disassembly system. In the previous stage, the disassembly level and structure were defined. Technical means that can execute the process and fulfil the system functions have been found. Now the main issue is to optimize the concept and to determine reliable equipment for the final lay-out. In this context, the embodiment design is characterized by continuous deliberation and verification of the temporary results obtained. This phase is split up into two sub-stages to make the process more transparent and to achieve final satisfactory results. The economic and technical issues should be considered and evaluated two times to ensure that the disassembly system meets all the necessary requirements. As can be seen from Figure 5.3, this phase also involves the arrangement of work stations, their integration into a disassembly line, its optimization and ends with a representation of a definitive lay-out.

The **detail design** means finalizing the definitive lay-out and completion of production documents with instructions. It also involves the design of the required disassembly tools, units and machines that fulfil the functions of the disassembly stations and the complete system. Through this step the entire design process is accomplished. This is followed by the **implementation phase** and finally the consequences of the introduction of disassembly systems should be worked out.

## 5.4 Structure of disassembly systems

In this section, the structure of a general disassembly process and system will be looked into. The aim is to give an idea of how disassembly systems can be arranged, and what the most important sub-systems and units are. In addition, we shall clarify what happens in a normal disassembly sequence and how the entire process is executed. For this purpose we will start with a black box model of a disassembly system, see Figure 5.5. It consists of common elements that characterize any technical system as described in the theory, see Chapter 3.

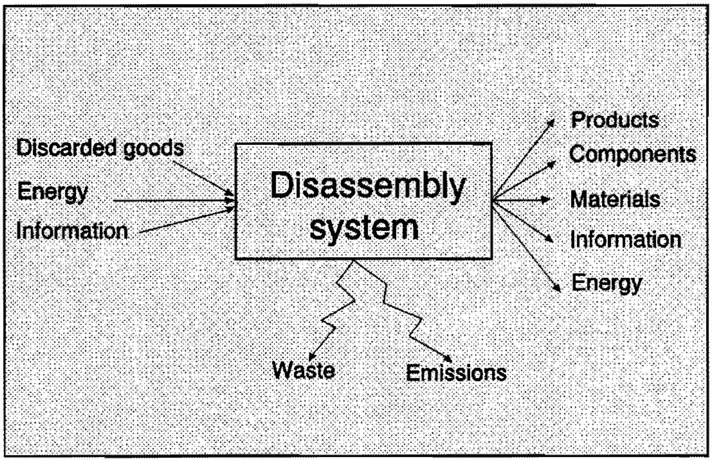



Figure 5.5: A black box model of a disassembly system.

The overall function of a disassembly system is to disassemble the discarded goods in order to reuse them in an optimal way and reduce their environmental impact. This means that the input variables must be converted into desirable output variables, while the overall function is fulfilled. As can be seen from the above figure the input variables of a general disassembly system are:

- o Discarded goods.
- o Energy.
- o Information.

The discarded goods are regarded as input of compounded parts and materials that should be recovered. For this purpose comprehensive information is required concerning the precise number of disassembly goods, their structure, quality, what the valuable and poisonous components and materials are, and the optimal disassembly process for their recovery. Obviously, energy is required to transform the compounded goods into valuable outputs. During the disassembly process, these input variables are converted into desirable outputs like:

- o Secondary goods.
- o Secondary components.
- o Secondary materials.
- o Information.
- o Energy.

The secondary goods, components and materials are the products of the transformation process. They can be used for a secondary production or can be sold to the customers. The information which is obtained concerns the reduction of discarded goods and design of a new generation "green" goods. In addition, energy can be produced, for instance, by the burning of fractions that can not be reused. However, this should not lead to environmental pollution. In other words, the environmental issues should always be fulfilled. Besides desirable outputs, unwanted outputs that should be minimized are generated during the disassembly process like:

- o Emissions.
- o Waste.

A disassembly system should include the necessary sub-systems, which must be capable of performing the desired sub-functions to fulfil the overall function. There are many disassembly sub-systems that can be found at different levels of the system's hierarchy. The highest level includes the most significant disassembly sub-systems given in Figure 5.6.

- o The *planning sub-system* should provide comprehensive information about the discarded goods and establish a disassembly plan. This system should be capable of recognizing a defined discarded good and to determine the operations that have to be performed in order to accomplish the entire disassembly process. In addition, the disassembly strategy and level must be determined. This implies a clear plan about the required disassembly operations, when a good should be sent to a shredder and to what extent it should be proceeded with separation. Furthermore, this system should determine the deviations in disassembly as a result of changes in a product during its useful life. The auxiliary actions that should be taken to compensate these anomalies should also be specified. For this purpose the necessary information should be collected and displayed in a table, which would facilitate the production process planning. This process can also be automated resulting in an advance CAPP (Computer-Aided Process Planning) software tool. Table 5.1 gives us an idea about the most important information which should be provided. As can be seen, it involves all the data required to develop a reliable disassembly process. It includes the determination of the product's structure, possible deviations during usage and corresponding disassembly strategy. Besides that, extensive information concerning the used join techniques is required to define the necessary disassembly equipment. Concerning the main types of joints that have been used in the practice, one can refer to the survey given by Andreasen [1988]. In addition, more precise information about all different types of joints, which are used in practice, can be found in the VDI [1990] catalogues. Furthermore, the joints are divided and the particular details are shown. This would contribute to develop the most feasible disassembly plan providing the desired results.

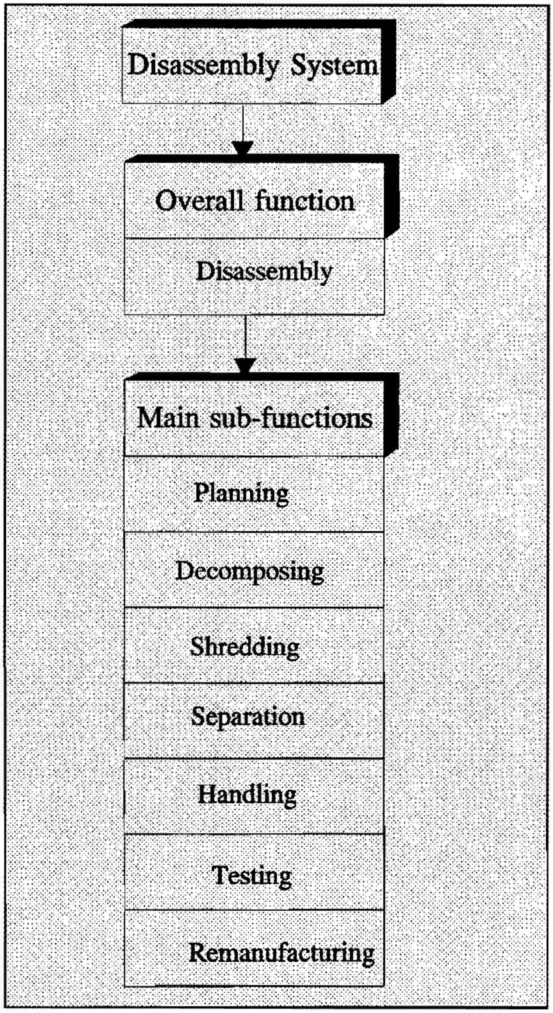


Figure 5.6: Disassembly sub-systems.

Table 5.1: A disassembly process planning chart.

| Name of a good | Structure | Disassembly strategy | Main joints | Possible deviations | Required disassembly tools and positions | Remarks |
|---|---|---|---|---|---|---|
| 1 | | | | | | |
| . | | | | | | |
| N | | | | | | |

o The *decomposing sub-system* includes all necessary work stations and equipment for accomplishing disassembly tasks for a wide range and type of discarded goods.

o The *shredding sub-system* involves the shredder and the associated equipment as a control panel, transport conveyors, etc. Its main task is to brake down a product into a number of fractions that can be easily separated and reused afterwards.

o The *separation sub-system* separates the various production streams, generated by disassembling or shredding, into pure material fractions. For this purpose the system includes various separations sub-systems, which will be discussed later on.

o The *handling sub-system* includes all operations associated with the transport between the work stations, positioning, clamping, unclamping, etc.

o The *test* and *remanufacturing sub-systems* imply auxiliary functions necessary for the recovery of components (sub-assembly) to a specified quality level.

The arrangement of a disassembly system begins during the conceptual design phase when the sub-functions are defined and solutions are found to fulfil them. As was emphasized before, the structure of a good is significant for the disassembly system lay-out. The structure determines the disassembly alternatives, the choice of sub-systems, the number of required work stations and their arrangement. It is obvious that the conceptual design of the disassembly process and system must be executed simultaneously with the good's analysis and determination of the assembly strategy. Only in this way, the most feasible disassembly system can be developed.

At the current stage of disassembly, a lot of problems have been identified. The lack of information concerning the discarded goods and their unfriendly design have been recognized as serious obstacles for the design of an automated or robotized disassembly system. This is the reason that the aim is to design an efficient and reliable system rather than a fully mechanized or automated system. For instance, human operators can carry out a visual inspection of parts that are disassembled. They are able to recognize a certain good and to execute even unidentified disassembly operations. This would reduce disruptions and increase the total technical performance of the system. Such complicated disassembly operations, caused by deviations in good's structure, can not be performed by advanced accurate machines or robots. It can certainly be concluded that the present disassembly systems need to involve a mix of manual and mechanized work stations in order to be efficient. The composition of such systems can be compared with the representation of assembly systems in a three dimensional grid, as was shown in Figure 3.5.

For decades the assembly process has been improved which has led to design and implementation of flexible assembly systems in practice. The main role in this development is held by the product design, which is executed in an assembly-friendly way. Concerning current disassembly, it is assumed that the most feasible configuration will mainly consist of manually equipped disassembly positions with automated transport between them.

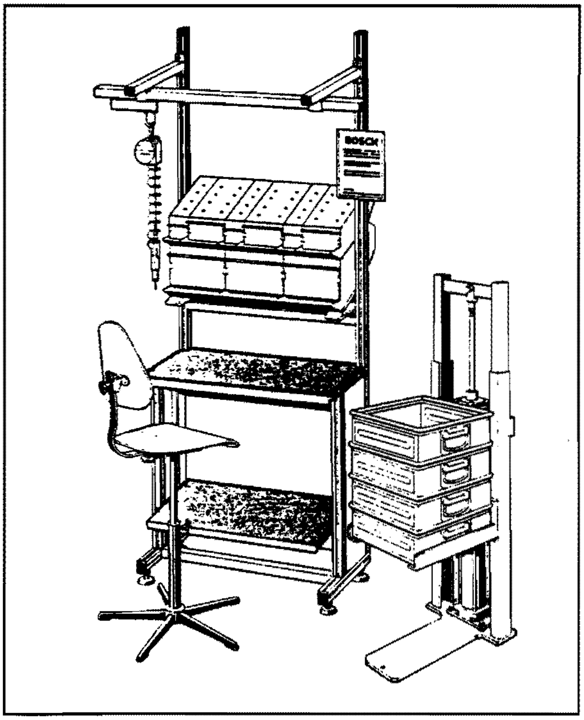


Figure 5.7: An equipped manual work station for disassembly [Loter, 1982].

For instance, Figure 5.7 represents a manual work position. The operator possesses all necessary tools for the execution of the assigned disassembly operations. The required information concerning the disassembly sequence and how it should be executed must be supplied. This involves the issues given in Table 5.1. Comprehensive information would assure an accurate, fast and efficient disassembly process. In addition, every work position is equipped to perform various operations, so that the discarded good can be positioned, oriented and fixed with minimum efforts on the part of the operator. Some of the common tools required for this purpose are:

- o Rotating table.
- o Clamping mechanism.
- o Pneumatic screw driver.
- o Pneumatic cutting device.
- o Trays.
- o etc.

In addition, some automated disassembly units can be introduced if this increases the system efficiency. They should be reliable, flexible and capable of carrying various disassembly operations for a wide range of discarded goods. For this purpose, some pick-place manipulators can be introduced, see Figure 5.8. Such manipulators can be designed simply by using separated translation and/or rotation units. The advantage is that such units can easily be rearranged for the execution of various disassembly tasks. In addition, they have a simple control and are truly reliable.

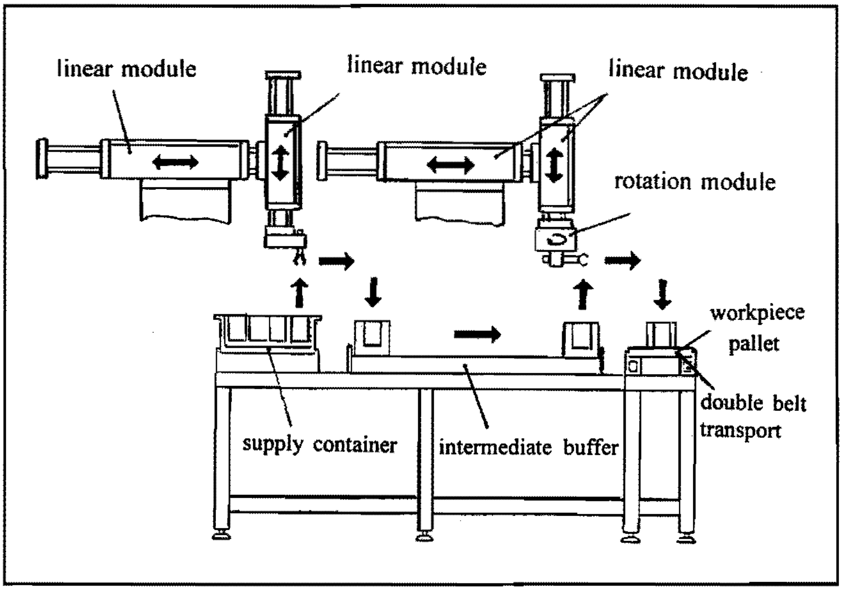



Figure 5.8: Pick and place units.

The number of work stations needs to be integrated into disassembly work sectors and into complete disassembly lines. This can be accomplished by means of various configurations. The work positions equipped can be grouped in sequential, parallel and mixed configurations. The kind of disassembly system to be designed depends on a number of factors, which are considered during the design process. Some of them are related to the discarded good, such as:

- o Assortment of goods.
- o Structure of goods.
- o Components of goods.

Others depend on the required process steps and the corresponding technical means like:

- o Disassembly sequences and number of operations.
- o Available disassembly tools.
  - * existing;
  - * knowledge about the development of new tools;
  - * integration of tools;
- o Disassembly system lay-out.

In addition, there are other factors related to economic, environmental and social issues like:

- o Investment policy.
- o Pay-back period.
- o Fulfilment of legislation requirements.
- o System's capacity and flexibility in order to fulfil the annual rate.

When designing disassembly systems, a balance should be made between the factors mentioned above. The aim is to design and implement a disassembly system that fulfils the following important criteria [Sanders, 1990]:

- o High productivity.
- o High flexibility.
- o Good working environment.
- o Economic efficiency.
- o Fulfilment of environmental needs.

The implementation of such a system is only feasible if the total productivity is increased, the ergonomic conditions are improved and the environmental impact of the discarded goods is reduced. In other words, the issue is not only to regain the value added to discarded goods and materials but also their environmentally-friendly processing and recycling.

The aim of the disassembly sub-systems is to perform the compulsory and desirable operations with respect to the requirements that have been established during the market investigation and clarification of the task. In other words, the sub-systems execute all necessary disassembly operations according to the determined disassembly strategy.

It has been highlighted that full disassembly is not profitable and that at a defined stage the goods are sent to a shredder. To accomplish the complete disassembly process a shredding sub-system is required, see Appendix 5.2. During shredding, the goods are cut on random lines. The output flow consists of various materials. They need to be separated to be used as quality materials, which are compatible to the raw materials. Some separation techniques are described in Appendix 5.2. Every single case requires accurate examination to determine the correct choice of the shredder and separation techniques. Only long-term experience in this field supported by continuous research can help us find the accurate solution to a defined problem.

## 5.5 Development of advanced disassembly plants

Every design process is performed to satisfy determined needs and requirements. They usually impose restrictions that define the level of abstraction and the properties of the new system. In practice, designers usually take an existing system as a starting point and redesign it to fulfil the requirements. This approach does not consider the idealized situation. Creation of an ideal model is needed to give a concept of the opportunities to introduce more advanced systems in the near future. It should be emphasized that in principle there is no completely ideal model of an artifact. Every design can be improved although it may once have been considered an ideal one. In other words, the ideal design of today will be the subject of redesign of tomorrow. This hypothesis can be proved by regarding the continuous evolution of various technical systems. For instance, consider the evolution of a wheel to the most advanced automobile system of today.

The aim of an ideal design is to show what can be achieved in the near future if the requirements of today are changed. Considering the reuse of goods and materials, we have seen that the disassembly-unfriendly product design is the main obstacle for the development of an advanced disassembly plant. However, it is assumed that the problems associated with design for easy disassembly will be solved, which will change the consequences concerning the design of disassembly systems. In this case, the discussion can start with considerations about:

- o Who will perform disassembly: the producer or autonomous plants?
- o What will the organization for reuse be: centralized or decentralized?

Current results show that companies, which are engaged with both production and recycling of its own products, are facing difficult problems and are not profitable. An example is Siemens Nixdorf; after years of recycling of its own goods, this activity has been contracted out [Didde, 1994]. The same tendency can be observed by Philips; his experimental factory (Mirec) for the reuse of electronic goods is a subject for a move to an independent recycling company. Besides that, an increasing number of "final" products have to be recycled at the place where the last customer has discarded them [Cairncross, 1992]. For instance, products imported in Europe have to be reused and disposed of at their end destination. Consider the huge amount of industrial products coming from Japan. It would be unrealistic to think that after usage, all these discarded good will be transported back to their producers. These facts imply that the future belongs to autonomous and flexible plants able to disassemble, recycle and reuse a wide range of discarded goods. While every one of these plants is performing disassembly, some of them should be specialized in the execution of special operations. For instance, consider the recycling of freon or testing of various electric motors or engines. These operations associated with the entire reuse of products should be integrated and executed in a specialized plant. This means that the trend is decentralized recycling but integrated execution of special functions.

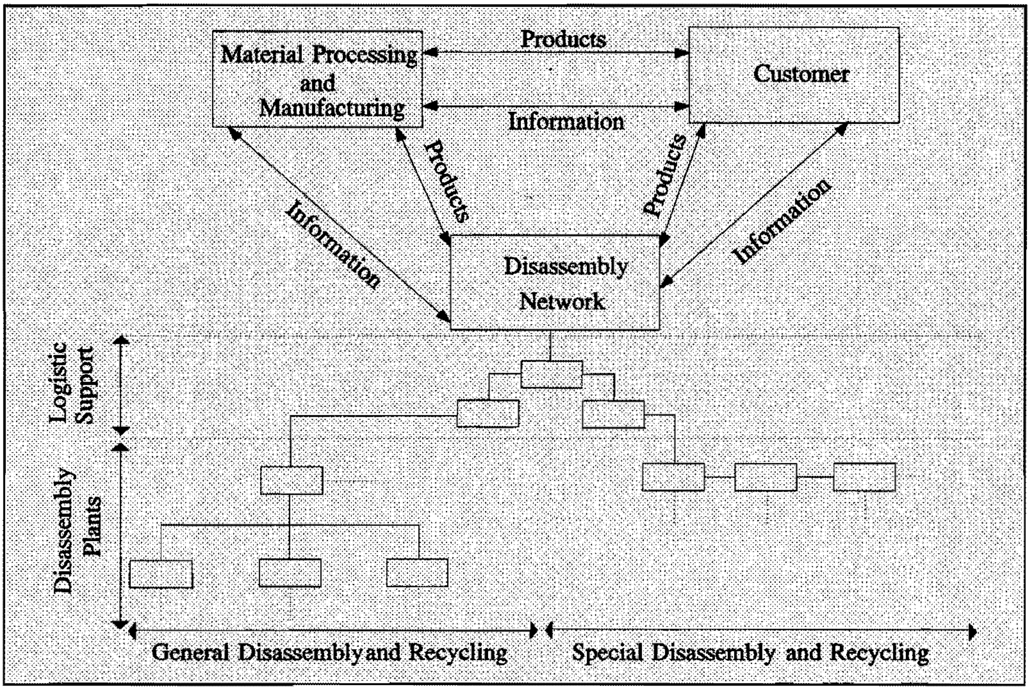



Figure 5.9: Recovery friendly production model.

It is our hypothesis that in the future more disassembly plants will get into the business of the reuse of goods. Their number and organization will be determined by the current need for reuse. This means that the goods are designed for disassembly and reuse, and that the required information is exchanged permanently in dual directions between all participants, see Figure 5.9. In other words, the producer collects information from the market to satisfy customer and legislation requirements. Then the producer designs products for ease of disassembly and supplies the disassembly plants with the information required to accomplish the disassembly process. These plants also receive information from the market concerning the current needs and return information and products to manufacturers and consumers. It results in a number of disassembly plants that perform various activities. The reliable exchange of information between them is significant. This implies the recycling of particular products and materials from specialized plants. The network of disassembly plants will close the loop of the product life cycle and ensure that products and materials will be reused with a certain profit and environmental benefit.

As was mentioned already in Chapter 2, another hypothesis predicts that in the future most of the products will be leased [Navinchandra, 1993]. In this way, one can sell the functionality of a product to a customer, but lease the parts and materials included in a product. This means that, when a customer discards a product, it is returned to the manufacturer who decides how to proceed with reuse. This model, called sustainable leasing, may be applicable to durable goods. However, for consumer goods it is unrealistic to think that a customer would appreciate the leasing concept, because he would like to possess the complete product and not just its functions. Our hypothesis is that even if some products are leased, they will need to be processed after a defined period of time. In addition, most of the consumer goods will be sold to the customers and therefore disassembly plants will exist regardless the sale concept. This is the reason that the recovery friendly production model should be regarded. In addition, this model includes the sustainable leasing model where the product life cycle loop is closed between the manufacturers and the customer, as the disassembly plants are involved with manufacturing ones.

Based on the recovery friendly production hypothesis, the structure of an advanced disassembly plant can be considered. There is no doubt that the level of mechanization and automation should be increased. The goal is to lighten or replace human labour by computer-controlled machines and robots only if the total system's productivity and product quality is increased. The costs of human labour increases steadily, which makes the introduction of automation more attractive. Automation is supposed to provide a reduction of costs and to increase the quality of disassembled products. However, from a flexibility viewpoint, automation can be a retrograde step as there is no machine as flexible as a human being. With reference to this fact, an advanced automated disassembly factory will consist of mixed work stations. The automation should be concentrated on two main issues:

- Automation of the information processing.
- Automation of the shop floor.

Figure 5.10 represents a general model of an advanced disassembly plant. The discarded goods are delivered in random order, quantity and variety. They are unloaded and supplied automatically to the planning department. Here, the goods are identified and a procedure is assigned explaining how to proceed further. This includes the determination of the disassembly strategy based on the current data. The following options are possible:

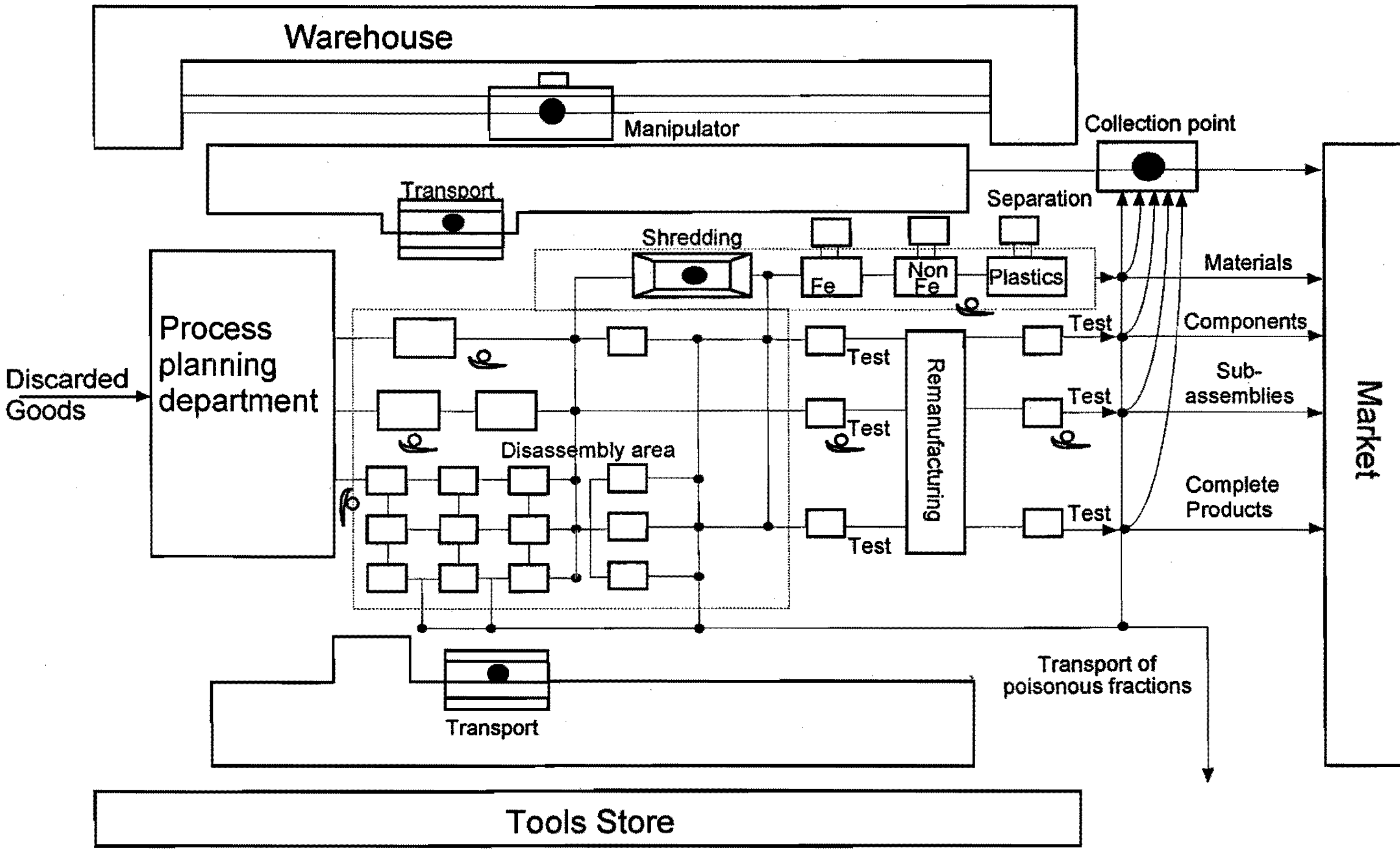



Figure 5.10: A disassembly plant's model.

- o Goods are sent for disassembly.
- o Goods are sent to the shredder.
- o Goods are stored in a warehouse for later disassembly.
- o Goods are sent to specialized plants.

After this step is accomplished, the resources are assigned that can carry out the prescribed disassembly operations. This is called scheduling, which means it is determined how the goods should be disassembled with the available machines and labour, and which disassembly sub-lines and cells are included. The information system should collect the information about the quality and quantity of disassembled goods, volume of materials, deviations during disassembly, etc. According to the orders, some products are transported to their end destination and others are stored in the warehouse. This means that the information system should be able to carry out all activities associated with information management, shop floor management, engineering design, maintenance, logistics and process planing.

The products that are supplied to the disassembly system go through a number of disassembly operations and/or are sent to a shredder. Within the disassembly system all handling and transport operations are automated. What the exact system structure will be, depends on many factors, which have to be determined during the clarification of the task. It can be concluded that to ensure flexibility, this system should involve a number of human operators and flexible robotized disassembly cells. This implies that the robotic cells should be able to disassemble a wide range of discarded goods. For this purpose they have to be monitored by a flexible control system and equipped with a number of associated pieces of equipment like:

- o Robot vision.
- o Image processing system.
- o Flexible tools.
- o Automatic exchange of tools.
- o etc.

Sophisticated operations such as the inspection of parts will mostly be carried out by human operators. This is the following step after disassembly where the parts are tested and remanufactured if required.

In the future, the products will be designed disassembly-friendly, so that most of the disassembly operations may be carried out by automated equipment and the materials can be separated during disassembly. This assumes that the use of a shredding system can be limited to special purposes as many products will be designed for material recycling only and not for component reuse. This is the reason that shredding systems will continue to have a place in the entire disassembly system structure and separation sub-systems will be included to separate various materials into pure fractions.

Finally, the products are transported automatically to the warehouse or for external transportation by means of belt conveyors, AGV and manipulators. In addition, all transport operations between the work positions, cells and lines are automated as well. Besides that, a tool store is involved for supplying the disassembly plant with the required tools.

This description shows that an advanced disassembly plant can function like the flexible manufacturing and assembly systems of today. However, for this purpose the product design must be changed and comprehensive information must be provided, which will be the main issue in the coming years.

## 5.6 Conclusions

There is no doubt that the enormous environmental problems caused by the increasing flow of discarded goods should be solved as soon as possible. In this context, the development and implementation of disassembly systems are recognized as major issues with respect to the reuse of discarded products and materials, and reduction of the environmental impact. However, because of many obstacles that have already been discussed, disassembly is considered a complicated process. This discourages companies from considering the recovery issue before the introduction of governmental rules. To reduce the level of indecision, a systematic approach is needed for the simultaneous analysis of discarded products, and design of the corresponding disassembly process and system. The aim is to show the opportunities this new trend has to offer and how they can be used to generate profit. Such a systematic approach should involve all important aspects that influence the design of disassembly systems. It should give a complete procedure to tackle and solve the recovery issues. The systematic approach should be applicable to all type of discarded goods, now and in the future.

The suggested systematic approach described in this dissertation is based on the available knowledge and experience in engineering design. Besides that, it has been extended with particular disassembly issues. In addition, new methods have been developed to solve particular disassembly problems within some phases of the design process. The proposed systematic approach involves the following main phases:

1) Collection of market information.
2) Clarification of the task.
3) Conceptual design.
4) Embodiment design.
5) Detail design.
6) Implementation.

To proceed through the steps, the designer should be acquainted with the segments of the engineering design concerning the disassembly issue, as have been discussed. Within every design stage, there are a number of significant steps that should be executed in a systematic way. This presumes introduction of suitable design methods. Some of them can be taken from engineering design science and others should be developed with respect to new particular issues.

The core of the suggested approach is the determination of the disassembly strategy. Most of the attention should be devoted to this step because it defines the disassembly subsystems, operations, their properties, profit and environmental benefit. For this purpose the method proposed in Chapter 4 has to be introduced. It helps the designer to develop a feasible concept for the optimal disassembly process, which is indispensable condition to proceed with the development of the corresponding disassembly system.

Using the suggested systematic approach along with the appropriate methods for analysis and design, makes the design process transparent, easy to understand and considerably reduces the level of uncertainty. The benefit of this systematic approach has been proven in practice, where satisfactory results have been recorded. Some practical experiences are described in the next chapter.

# Chapter 6

# Application of the systematic design approach

## 6.1 Introduction

Among other things, the aim of this research is to approach and solve some practical problems concerning the disassembly and recovery of discarded goods and materials. For this purpose the suggested systematic design approach has been applied in various companies for the development and implementation of disassembly systems. Three studies have been carried out with respect to various household appliances and electronic goods.

The first case concerns the recovery and recycling of refrigerators and freezers. The main issue is the processing of freon, while a maximum profit has to be generated from the recycled materials. During the design phase, the most efficient dismantling line among the feasible alternatives was developed. The suggested design concept was implemented by the company and is operating satisfactorily.

The optimal way to recover some electronic goods is described in the second case. Both cases deal with the recycling of consumer goods, which implies that a limited number of valuable components are involved. This is the reason that disassembly is usually limited to the removal of poisonous materials and to the generation of pure material fractions.

The third case shows how disassembly systems can be combined to process a wide range of discarded goods; household appliances as well as consumer electronics. The developed disassembly system concept for the selected goods was also implemented.

The following sections of this chapter describe in detail the design of the above mentioned disassembly systems.

## 6.2 The (re)design of a dismantling system for refrigerators

### 6.2.1 The discarded refrigerator

In response to the increasing flow of discarded goods, a company was established that is interested in the environmentally friendly processing of discarded refrigerators and freezers. It is well known that these household appliances use freon. According to experts, freon causes severe damage to the earth's ozone layer [Rowland, 1987; Stam, 1988; Scholtens, 1988]. The consequences are tremendous as the sun's radiation penetrates the atmosphere without being filtered by the ozone. This phenomenon is considered to be the main reason for skin cancer and other negative effects on people's health. The increasing public concern about this severe environmental damage resulted into the introduction of new governmental rules for the processing of refrigerators and other appliances using freon. The legislation requires the environmentally friendly processing of freon so that emissions to the atmosphere are avoided. Moreover, by 1995 all producers of refrigerators must substitute freon by other coolants, which will not cause environmental damage [VROM, 1992]. To promote this issue, the Dutch government has offered financial support to companies involved in the environmentally friendly recycling of refrigerators. Considering the new market opportunities, a pilot plant has been set up for the dismantling of refrigerators and the processing of freon. After that, the freon is neutralized by a specialized chemical company. The purpose of the recycling company is to conquer a new market and generate as much profit as possible from the compounded materials available in the discarded refrigerators while fulfilling the legislation rules, including the environmental aspects.

The distribution of materials in a refrigerator is shown in Figure 6.1. In general, the casings of refrigerators are made of sheets of steel or aluminum to form the outer shell and BS (butadiene-styrene) to form the inner shell. An insulating material is used between these sheets. In general, most of the refrigerators produced in the past used freon and a limited number used ammoniac as a coolant. According to the manufacturers, the production of refrigerators with freon is reliable and cheaper in comparison to other existing technologies. In addition, freon is safer as a coolant and has superior expanding properties than other possible expanding agents e.g. hydrocarbons. Therefore, freon is used almost exclusively in the present electrically powered refrigerators. As a heat transporting medium, freon is used in the refrigerating unit and as a vapour it is mixed with PUR to create a large heat resistance between the shells. This mixture contains 65% of the entire freon quantity. It is obvious that the most important contribution to the protection of the environment is the processing and neutralization of freon, which is considered a hazardous material. The remaining refrigerator's materials, like ferrous, non-ferrous, plastics, glass and foam should be recovered to generate profit and to fulfil the legislation requirements. In this case, the most valuable materials are copper, aluminum and ferrous material. Copper can be found in the cables and in the refrigerator's compressor, while aluminum is a part of the refrigerator's case. In addition, the refrigerators are made of a number of plastic materials, like BS, PVC, ABS and PUR foam. The separation of such mixed fractions after shredding is very difficult. Therefore, if these materials have to be recovered, it is recommended one separates them before shredding by means of disassembly (dismantling). In this way, pure fractions can be obtained resulting in higher output expressed in monetary value. These activities depend upon the market demands and economic considerations. In addition, the compressor can be considered a valuable component, which can be reused after testing and remanufacturing. If the quality standards can not be fulfilled, the copper fraction of the compressor can be recovered. To accomplish these tasks, disassembly operations have to be applied. However, the compressor and the other refrigerator's sub-assemblies (material fractions) are assembled by means of a number of disassembly unfriendly joints, most of which are fixed. This makes the separation of components and materials by means of disassembly labour intensive and results in high costs.

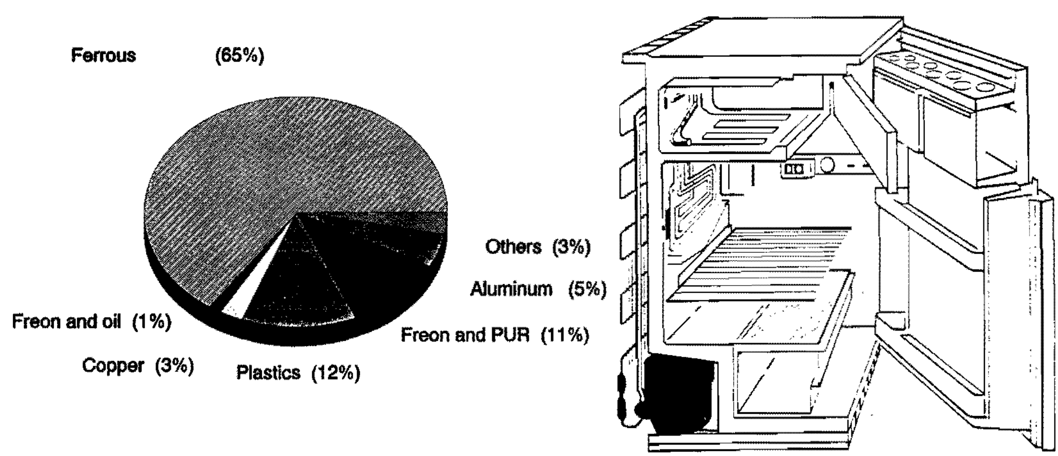



Figure 6.1: Distribution of the mass of materials in a refrigerator.

Concerning the above analysis of the refrigerator, the following conclusions can be drawn:

- o Refrigerators are more suitable for material recycling than for component reuse.
- o While recovering refrigerators, the main environmental issue is the extraction and neutralization of the freon.
- o The main economic issue is to obtain pure material fractions with the minimum of recovery costs.
- o Refrigerators are very difficult to disassemble since most of the joints are realized by spot welding and screws.

At the start, the firm we investigated was able to process about 20,000 refrigerators per year, while the number of discarded refrigerators in the Netherlands and the Northern part of Belgium is estimated at about 600,000 per year. This huge flow of discarded goods has pushed several small companies to start with the dismantling of refrigerators, resulting in an increasing competition in this field. Therefore, an improvement of the firm's recovery facilities and the introduction of an efficient dismantling process and system is required to be competitive in the market. The following sections describe the initial dismantling process in a factory and how it has been improved by applying the suggested systematic approach, which was described in Chapter 4 and 5.

### 6.2.2 Description of the initial dismantling process

To fulfil the legislation requirements and economic goals, the company regarded set up a dismantling (disassembly) system for discarded refrigerators. Because of a lack of information and experience with disassembly, the dismantling facilities were labour intensive, resulting in high recovery costs and low revenues. This required the analysis of the initial dismantling process in order to draw a clear plan for improvement. The lay-out of the initial dismantling system is shown in Figure 6.2. It contains 13 work positions served by 15 workers. The production process is carried out as follows.

The diverse types of refrigerators are delivered in containers. Six containers are located at the first work position; these containers are on steel bars and are lined up next to each other. A powered conveyor is located at the first position along the containers; this is the beginning of the dismantling line. In position 1, a worker unloads the refrigerators from the containers. Next, he removes the doors and unfixed inside materials, and cuts the cables, which are put in small containers. The detachment of the door is accomplished by using a hammer. If necessary, two other workers, who are concerned with the internal transport, help at position 1.

The refrigerators are moved by the powered conveyor to the second work position. There, another operator removes refrigerators with ammoniac as a coolant from the line. These refrigerators are recycled by another firm. By using an absorbing pump, the operator extracts the freon and oil from the cooling system. The absorbing pump is equipped with a special device that makes a hole in the compressor and simultaneously closes the area around the hole, so that the freon can not escape during the absorption. The duration of this activity depends on the quantity of freon available in the cooling system. This operation is considered a bottle neck.

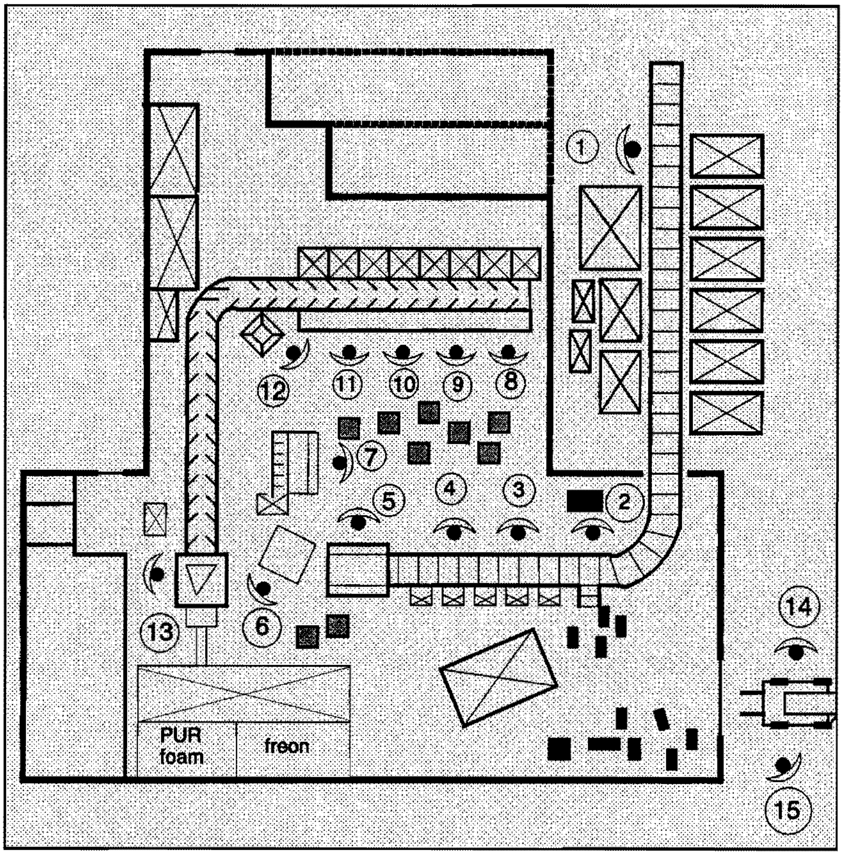


Figure 6.2: Lay-out of the initial dismantling system.

In the third position, a worker cuts the attachment of the compressor by using a power-saw. The disassembly of the compressor is not possible because of unfriendly joints and a wide variety of refrigerators, therefore the compressor is removed by using destructive techniques. After accomplishing this labour intensive operation, the worker removes the condenser using a hammer and puts it in a container. Since the conveyor is not powered from this position, further handling is accomplished manually.

In the fourth position, an operator removes the thermostats and joints that attach the doors. In addition, he positions the refrigerators for the saw machine. In the fifth position, the refrigerator is sawed apart into three parts. The panels are picked from position 5 and pelletized at position six. The side panels are put on a table so that the next worker can reach them. Furthermore, the doors that have been transported in containers from the first position are passed to the next position.

In the seventh position, a worker puts the side panels and doors in a press, which cuts off the edges of the panels and doors. These edges are removed as they usually contain non-recyclable materials. Then, they are transported by a conveyor to a container and considered to be waste.

The work positions from eight to twelve are supplied with pallets containing the refrigerator panels. Four workers manually separate the PUR foam from the sheets of steel or aluminum. The PUR foam is thrown on a powered conveyor and it is reduced into a number of small fractions. Then the PUR is transported to the degassing installation. In addition, the ferrous and non-ferrous materials are put in corresponding containers.

Position thirteen represents the degassing installation for the processing of the freon. The installation is able to process about 98% of the total freon volume. It is operated by a worker who also observes the electromagnetic belt for the separation of ferrous materials. In addition, positions fourteen and fifteen represent operators concerned with different internal transport tasks. If required, they support the operators in various work positions.

Based on the dismantling process described above, the company was not able to generate profit. The costs made to process the refrigerators were in balance with the sum of the governmental financial support and the obtained revenues. The described production process displays a number of disadvantages. The main problems are related to the used process and lay out. The specific problems that were experienced are:

Position 1:

- o The unloading of the refrigerators is difficult, because the containers are at a lower level than the conveyor.
- o The containers used for the non-fixed materials are behind the worker so he expends a lot of power.
- o The containers with the doors have to be transported to position 6 which makes for bad logistics.

Position 2:

- o The positioning of the absorption tool is difficult as the refrigerator is not fixed at the work position.

Position 3:

- o A lot of effort is spent in cutting the attachment of the compressor.
- o After cutting the attachment, the compressor falls down and must be lifted manually and thrown into a container that is not located near the worker.

Position 5:

- o During sawing, freon escapes from the foam which diminishes one of the goals of recovery.

Position 6 and 7:

- o There is manual transportation of doors and panels to positions 8-12, which results in undesired inventories.
- o The work is labour intensive and inefficient.

Position from 8 to 12:

- o Highly intensive manual operations that do not fulfil the requirements concerning the generation of pure material fractions.

Considering the above, it is obvious that the company was pushed to introduce a new dismantling process and system. The central issue became how to develop an upgraded and profitable dismantling process, so that a highly competitive business could be achieved. In this context, the following issues are deemed to be important:

- o Increase of the percentage of recycled materials.
- o Increase of the total productivity.
- o Facilitation of the operator's task at every work position.
- o Automation of the material flows and mechanization of the work positions.
- o Keeping the existing or increasing the percentage of the processed freon.

To fulfil the above issues, the knowledge of special processes and equipment should be used for the design of disassembly systems, as was explained in Chapter 3. This implies that modern technologies and equipment have to be used for disassembly and recovery purposes. Some of them can be found as modules of current operational production systems. The designer's task is to recognize and choose the technical means that can be used as segments of the required recovery and disassembly systems. In this way, it is possible to design and implement the disassembly system for refrigerators with a minimum of efforts and costs.

The following section describes the application of the suggested systematic approach for the (re)design of disassembly systems. It is applied to fulfil the company's goal and to provide the achievement of desirable results.

### 6.2.3 Systematic (re)design of the initial dismantling system

The systematic design of disassembly systems starts with a comprehensive collection of **market information**. It concerns various important factors for the recovery of discarded goods, like legislation rules, environmental issues, available technologies, market prices and logistics. In this context, the following fundamental questions are essential:

1) *Why* should disassembly be applied?
2) *What* should be disassembled?
3) *How* should the disassembly operations be carried out?

The first question concerns the legislation, economic and environmental aspects. It defines for what reason the discarded goods should be recovered. Two issues are important in this case:

- o Increasing the recovery percentage of secondary materials.
- o Decreasing the environmental impact of discarded goods.

In other words, the recovery and environmental requirements, which are imposed by the legislation, should be fulfilled because there is no way to avoid them. To accomplish this task, one has to find out *what* components or material fractions have to be disassembled and recovered. For this purpose a rough analysis of the discarded goods has to be carried out, as was described in section 6.2.1. The aim is to determine the market price and disposal cost of every material and component that can be processed. According to the developments in the market and the services offered by specialized recycling firms, the company selects some components and materials for recovery in order to generate the desired profit, like:

- o Components:
  - * Compressor.
- o Materials:
  - * Ferrous.
  - * Non-ferrous.
  - * Some plastics.

In addition, considering the environmental issue, the freon and oil should be extracted and processed. By accomplishing the above analysis, an estimation can be made about the expected profit and environmental effects. In addition, considerations should be made about the existing logistics, clients and governmental financial support. If they are found to be favorable it would mean the recovery of refrigerators is a profitable activity.

During the **clarification of the task**, the analysis of discarded goods should be continued with the gathering of information about the types of joints, valuable materials and poisonous materials that have been used. To this end, products' drawings and pictures should be used that define the structure of the discarded goods as clearly as possible. If this is not possible for any reason, the missing details should be specified during the disassembling process.

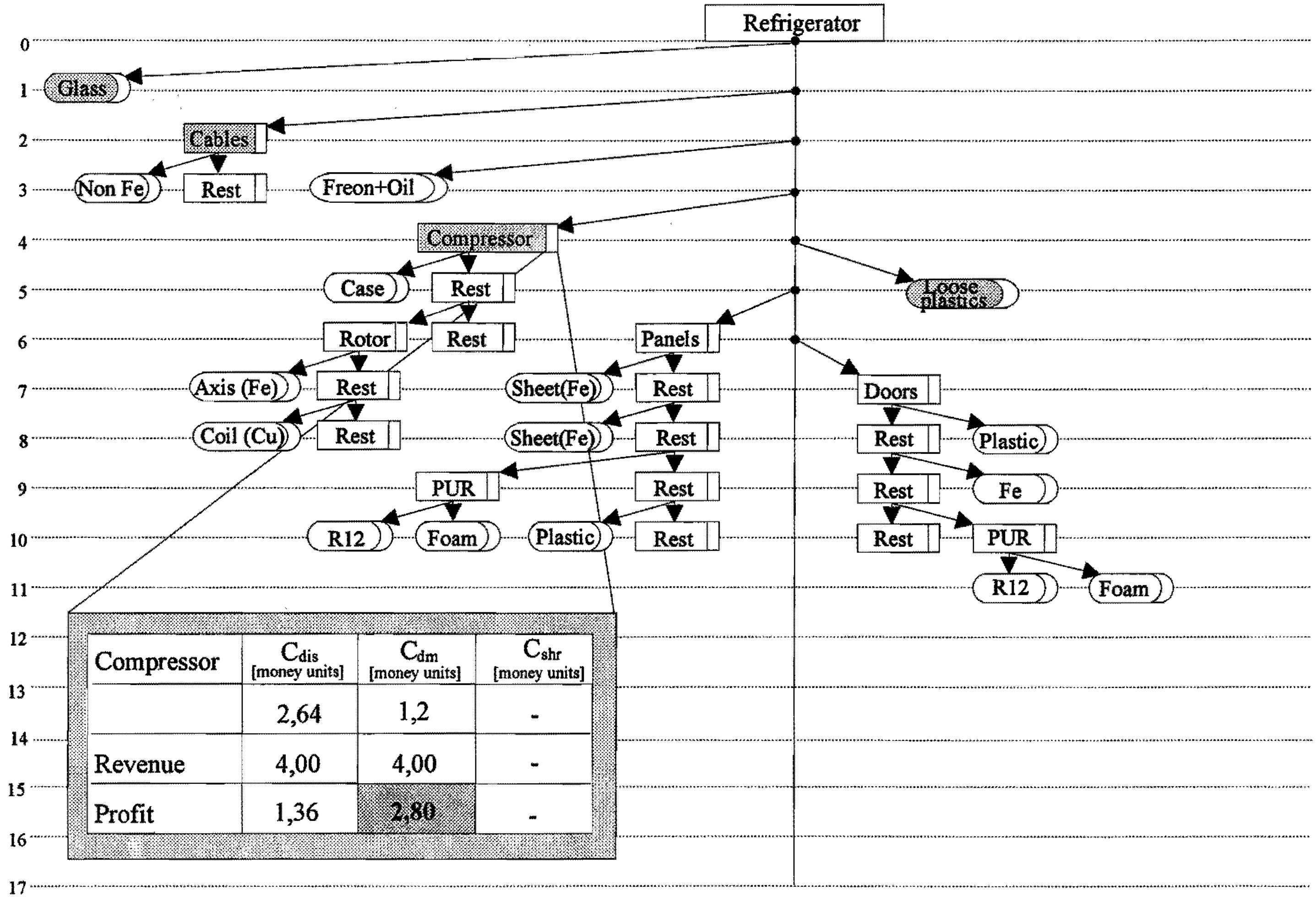
Based on the refrigerator analysis, the disassembly strategy should be established. It gives the answer to the third fundamental question; *how* should the disassembly operations be carried out in the most profitable way. For this purpose the disassembly strategy has to be determined, as was explained in Chapter 4. The first step is the generation of the number of feasible disassembly alternatives that can be accomplished by using the AND/OR graph. It is emphasized that the graph only involves the disassembly operations that generate the desired output flow. At the beginning it should be clear which components and/or materials have to be recovered. In other words, the content of the output flow should be defined so that a maximum profit is obtained, while fulfilling the legislation. One can imagine that some of the disassembly operations can be ignored because their execution does not contribute to the generation of the desired output flow. Other disassembly operations should be omitted because of technical or logistical considerations. In addition, some disassembly operations should be executed before others, because of the restrictions imposed by the product's structure. In this way, the number of disassembly alternatives and operations can be reduced considerably. Without this simplification, the search for the optimal disassembly plan becomes extremely difficult and impossible for execution, as was explained in Chapter 4.

Taking into account the above considerations, the disassembly strategy for the recovery of refrigerators should be determined. The reduction of the disassembly alternatives can also be done by specifying the operations that have to be executed at the beginning of the disassembly process. In this context, the freon has to be extracted before proceeding with the disassembly of the compressor. In addition, the compressor has to be compulsorily disassembled because it is considered a valuable component for further recovery and because it may damage the cutters of the shredder. In addition, it is recommended that one removes the glass and non-fixed plastic parts before shredding in order to increase the purity of the obtained secondary materials. Besides that, there are other constraints due to technical or logistical requirements. Considering these specific requirements for the disassembly of refrigerators, the AND/OR disassembly graph can be generated. Figure 6.3 represents one of the graph's branches, while the other disassembly alternatives are given in Appendix 6.1. It can be seen that after every disassembly step a new sub-assembly, component or material fraction appears. The generated disassembly alternatives only represent feasible disassembly sequences, as the impossible alternatives are rejected. After the feasible disassembly alternatives are established, it is followed by the determination of the profits for every disassembly step. This results in the determination of the optimal disassembly depth (level) and sequence by which the maximum profit is generated. The optimization problem, described in Chapter 4, can be expressed by:

$$P_{ref} = \sum_{i=1}^{n} (R_{ref,i}) - \sum_{i=1}^{n} \min (C_{dis,i}, C_{dm,i}, C_{shr,i}) - C_{mis} \qquad \textbf{(6-1)}$$

where the symbols are the same as given in Chapter 4, besides the new symbols that have the following meaning:

| | | |
|---|---|---|
| $P_{ref}$ | - | total refrigerator's recovery profit. |
| $R_{ref}$ | - | refrigerator's revenues. |




| Compressor | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 2,64 | 1,2 | - |
| Revenue | 4,00 | 4,00 | - |
| Profit | 1,36 | 2,80 | - |

Figure 6.3: Disassembly graph: alternative 1.

Before considering all feasible recovery options, the compulsory disassembly steps in the disassembly plan should be included. As was explained, these steps are the extraction of freon and the removal of the compressor. Then equation (6-1) results in:

$$P_{ref} = R_{com} - \min(C_{dis,com}, C_{dm,com}) + R_{fr} - C_{fr} + \sum_{i=3}^{n} (R_{ref,i}) - \sum_{i=3}^{n} \min(C_{dis,i}, C_{dm,i}, C_{shr,i}) - C_{mis} \quad \textbf{(6-2)}$$

where:

| | | | |
|---|---|---|---|
| where: | $R_{com}$ | - | compressor's revenue |
| | $R_{fr}$ | - | freon's revenue (negative) |
| | $C_{fr}$ | - | freon's processing cost |
| | $C_{dis,com}$ | - | compressor's disassembly cost |
| | $C_{dim,com}$ | - | compressor's dismantling cost |

After these two compulsory steps are completed, disassembly should only be applied if higher revenues can be obtained. For this purpose, the revenues and corresponding costs should be considered until all the refrigerator's parts and/or material fractions are separated. For instance, consider the recovery of the compressor. The profit after the removal of the compressor from the refrigerator is given by:

$$P_{com} = R_{com} - \min(C_{dis}, C_{dm}) - C_{mis} \quad \textbf{(6-3)}$$

After substitution of the numeric values, the recovery profits can be calculated, see Table 6.1. It is emphasized that the corresponding data are only used as an example. It can be seen that the highest profit is 2.80 [money units] and it is obtained by dismantling. The shredding option is not considered, as it is not applicable in this case.

Table 6.1: Recovery of the compressor.

| Compressor | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 2.64 | 1.20 | - |
| Revenue | 4.00 | 4.00 | - |
| Profit | 1.36 | **2.80** | - |

Next, we have the recovery of the compressor's case, rotor, axis and coil, as given in the disassembly plan represented in Figure 6.3. The obtained profits are calculated for every step and listed in the tables below. The following equations should be applied for:

1) Recovery of the compressor's case;

$$P_{com} = R_{case} - \min(C_{dis,case}, C_{dis,case}) + R_{com,rest} - \min(C_{dis,rest}, C_{dm,rest}, C_{shr,rest}) - C_{mis} \quad (6\text{-}4)$$

where:

| | | |
|---|---|---|
| $R_{case}$ | - | case's revenue |
| $R_{com,rest}$ | - | revenue of the remaining compressor's materials |
| $C_{dis,rest}$ | - | cost for the disassembly of the remaining compressor's fractions |
| $C_{dm,rest}$ | - | cost for the dismantling of the remaining compressor's fractions |
| $C_{shr,rest}$ | - | cost for the dismantling of the remaining compressor's fractions |

Table 6.2: Obtained profit.

| Compressor's case + rest | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 2.64 + 1.22 | 1.20 + 1.22 | - |
| Revenue | 4.10 | 4.10 | - |
| Profit | 0.24 | **1.68** | - |

2) Recovery of the compressor's rotor;

$$P_{com} = R_{case} - \min(C_{dis,case}, C_{dis,case}) + R_{rot} - \min(C_{dis,rot}, C_{dm,rot}) + R_{com,rest} - \min(C_{dis,rest}, C_{dm,rest}, C_{shr,rest}) - C_{mis} \quad (6\text{-}5)$$

where:

| | | |
|---|---|---|
| $R_{rot}$ | - | rotor's revenue |
| $C_{dis,rot}$ | - | cost for the disassembly of the remaining rotor's fractions |
| $C_{dm,rot}$ | - | cost for the dismantling of the remaining rotor's fractions |

Table 6.3: Obtained profit.

| Compressor's rotor + rest | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 3.86 + 0.80 | 2.42 + 0.80 | - |
| Revenue | 4.25 | 4.25 | - |
| Profit | -0.41 | **1.03** | - |

3) Recovery of the compressor's axis;

$$P_{com} = R_{case} - \min(C_{dis,case}, C_{dis,case}) + R_{rot} - \min(C_{dis,rot}, C_{dm,rot}) + R_{ax} - \\ - \min(C_{dis,ax}, C_{dm,ax}) + R_{com,rest} - \min(C_{dis,rest}, C_{dm,rest}, C_{shr,rest}) - C_{mis} \tag{6-6}$$

where: $R_{ax}$ - axis' revenue
$C_{dis,ax}$ - cost for the disassembly of the remaining axis' fractions
$C_{dm,ax}$ - cost for the dismantling of the remaining axis' fractions

Table 6.4: Obtained profit.

| Compressor's axis + rest | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 4.66 + 0.30 | 3.22 + 0.20 | - |
| Revenue | 4.33 | 4.33 | - |
| Profit | -0.63 | **0.91** | - |

4) Recovery of the compressor's coil;

$$P_{com} = R_{case} - \min(C_{dis,case}, C_{dis,case}) + R_{rot} - \min(C_{dis,rot}, C_{dm,rot}) + \\ + R_{ax} - \min(C_{dis,ax}, C_{dm,ax}) + R_{co} - \min(C_{dis,co}, C_{dm,co}, C_{shr,co}) + \\ + R_{com,rest} - \min(C_{dis,rest}, C_{dm,rest}, C_{shr,rest}) - C_{mis} \tag{6-7}$$

where: $R_{co}$ - coil's revenue
$C_{dis,co}$ - cost for the disassembly of the remaining coil's fractions
$C_{dm,co}$ - cost for the dismantling of the remaining coil's fractions
$C_{dm,co}$ - cost for the shredding of the remaining coil's fractions

Table 6.5: Obtained profit.

| Compressor's coil + rest | $C_{dis}$ [money units] | $C_{dm}$ [money units] | $C_{shr}$ [money units] |
|---|---|---|---|
| | 4.96 + 0.20 | 3.44 + 0.2 | - |
| Revenue | 4.50 | 4.50 | - |
| Profit | -0.66 | **0.86** | - |

In the same way, the recovery option for the other parts and/or material fractions can be found. After all options have been considered and the calculated profits are found they can be represented in a diagram as given in Figure 6.4. There we can see the optimal disassembly depth for the recovery of the parts and material fractions while generating the desired output flow. In this case, the optimal disassembly depth for the compressor is the second step. This implies the extraction of the freon and oil, and the removal of the compressor from the refrigerator. The optimal disassembly depth for the door is achieved by shredding in the first step, which means that disassembly is not profitable. The optimal recovery of cables is achieved in the first step by means of dismantling, after which they are sold to a processing company.

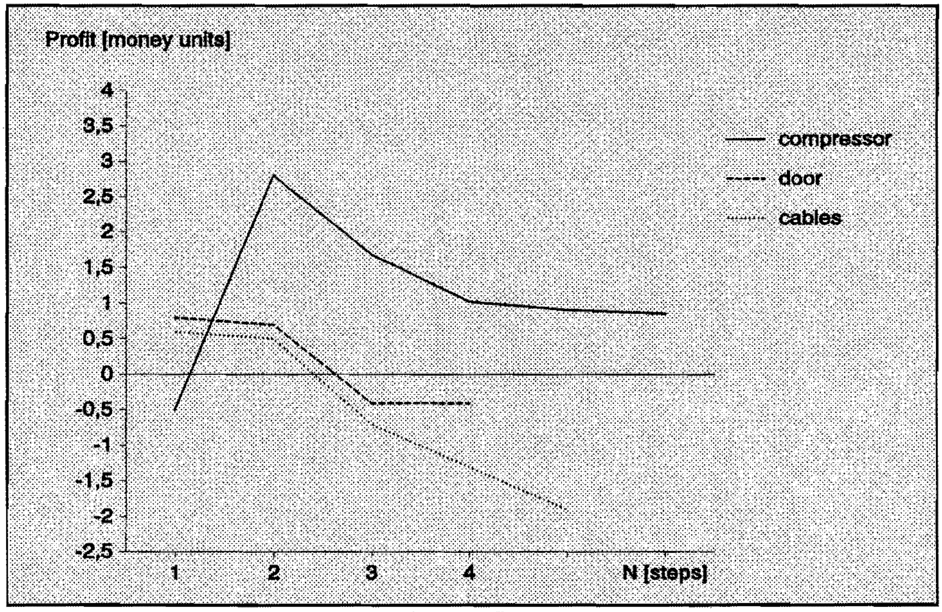


Figure 6.4: Disassembly profits of some components.

Based on the above considerations, the optimal plan for the recovery of refrigerators and freezers can be established, see Figure 6.5. It includes the following (dismantling) operations that should be executed before shredding:

1) Removal of glass.
2) Dismantling of cables.
3) Extraction of freon and oil.
4) Dismantling of compressor.
5) Removing the plastic box.

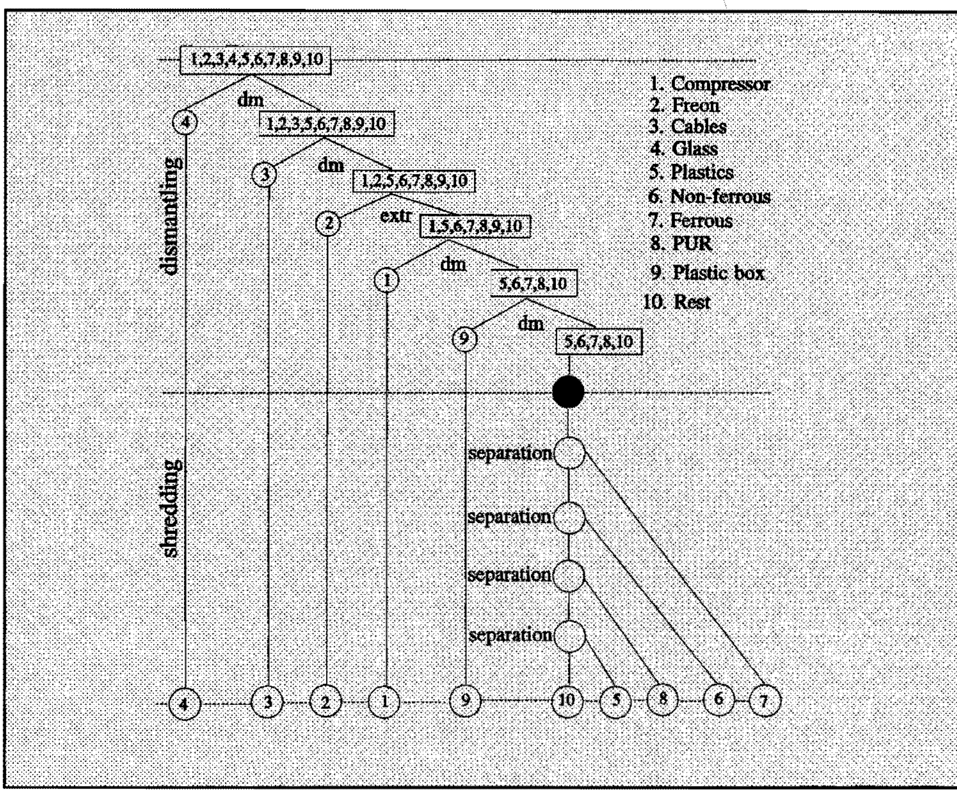


Figure 6.5: Disassembly process plan for refrigerators.

Then the refrigerators are shredded after which the mixed material fractions are separated in the most economic way. This is achieved by mechanical separation of the produced material fractions. For instance, ferrous materials are separated by permanent magnet belts, non-ferrous by an Eddy current installation, and the PUR is extracted and passed to the degassing installation by airflow. The remaining fractions usually contain mixed plastic materials that are treated as waste. Based on the selected disassembly plan, the maximum profit can be calculated. It is given by the following equation:

$$P_{max} = R_{com} + r_{fr}.m_{fr} + r_{fe}.m_{fe} + r_{gl}.m_{gl} + r_{cab}.m_{cab} + \\ + r_{al}.m_{al} + r_{pl}.m_{pl} - C_{dis} - C_{dm} - \\ - C_{shr} - C_{sep} - C_{mis} \ [money\ units] \quad (6\text{-}8)$$

where:

| | | |
|---|---|---|
| $P_{max}$ | = | maximum recovery profit per refrigerator |
| $R_{com}$ | = | compressors's revenue |
| $r_{fr}$ | = | freon's revenue per kilogram (negative) |
| $r_{fe}$ | = | ferrous material's revenue per kilogram |
| $r_{pl}$ | = | plastic material's revenue per kilogram |
| $r_{gl}$ | = | glass's revenue per kilogram |
| $r_{cab}$ | = | cable's revenue per kilogram |
| $r_{al}$ | = | aluminum material's revenue per kilogram |
| $m_{gl}$ | = | glass's mass |
| $m_{fr}$ | = | freon's mass |
| $m_{pl}$ | = | plastic material's mass |
| $m_{cab}$ | = | cable's mass |
| $m_{al}$ | = | aluminum material's revenue |
| $m_{fe}$ | = | ferrous material's revenue |
| $C_{dis}$ | = | total disassembly costs |
| $C_{dm}$ | = | total dismantling costs |
| $C_{shr}$ | = | total shredding costs |
| $C_{sep}$ | = | total separation costs |
| $C_{m}$ | = | miscellaneous costs |

The data that are required to accomplish this calculation are derived from the disassembly graph and presented in Table 6.6. The money units used for the purpose of this example are fictitious because of confidential considerations. After substitution of the numerical values of Table 6.6 in equation (6-13), the total profits of the disassembly plans are calculated and listed in Table 6.7. The difference in the generated profits can be explained with the variation of the purity of the obtained materials and the operational costs within the factory; the investments made for machines and the labour costs are approximately the same for all alternatives. It can be seen that the maximum profit is generated by plan 1. This means that the disassembly operations included in this plan should be selected and considered for implementation.

Table 6.6: Recovery chart of a refrigerator.

<table>
<tr><th>Component (material)</th><th>Material price [money unit/kg]</th><th>Component price [money unit]</th><th>Mass [kg]</th><th>$C_{dis}$ [money unit]</th><th>$C_{dm}$ [money unit]</th><th>$C_{sep}$ [money unit]</th><th>$C_{shr}$ [money unit]</th></tr>
<tr><td>Compressor</td><td>-</td><td>4</td><td>-</td><td>2.64</td><td>1.2</td><td>-</td><td>-</td></tr>
<tr><td>Freon</td><td>- 1.35</td><td>-</td><td>0.14</td><td>-</td><td>0.8</td><td>-</td><td>-</td></tr>
<tr><td>Ferrous</td><td>0.46</td><td>-</td><td>11.5</td><td>1.8</td><td>1.5</td><td>0.3</td><td rowspan="5">0.3</td></tr>
<tr><td>Plastics</td><td>0.26</td><td>-</td><td>0.22</td><td>2.2</td><td>1.9</td><td>0.6</td></tr>
<tr><td>Glass</td><td>0.02</td><td>-</td><td>0.2</td><td>0.8</td><td>0.7</td><td>1.0</td></tr>
<tr><td>Cables (Cu) *</td><td>2.03</td><td>-</td><td>0.15</td><td>1.4</td><td>1.2</td><td rowspan="2">0.7</td></tr>
<tr><td>Aluminum *</td><td>0.88</td><td>-</td><td>0.85</td><td>1.9</td><td>1.8</td></tr>
</table>

* - if required, copper and aluminum are separated together by means of Eddy current

Table 6.7: Recovery profits of the feasible disassembly plans.

| Disassembly plan | Short description | Profit [money units] | Difference in comparison with disassembly plan 1 |
|---|---|---|---|
| 1 | Removal of the glass, cables, freon and oil, compressor and plastic boxes. | **3.12** | - |
| 2 | Removal of the freon and oil, compressor, plastic boxes and cables. | 2.82 | The glass is shredded, which results in higher separation costs. |
| 3 | Removal of the freon and oil, compressor, plastic boxes, cables and glass. | 2.85 | The glass and cables are removed inside the factory. |
| 4 | Removal of the freon and oil, and compressor. | 2.41 | With the exception of the compressor, the remaining part of the refrigerator is shredded. |

Besides the disassembly strategy, the most important parameters of the disassembly system should be determined. As was highlighted before, the cycle time of the systems should be found, which will impose constraints on the selection of the equipment and system configuration. In this context, disassembly operations that last longer than the required cycle time should be executed in a number of disassembly work positions, so that the annual production rate can be fulfilled. The required cycle time can be found by equation (5-1), see Chapter 5. After substitution of the numeric values in this equation, a cycle time of 81 [sec] is derived. The calculated cycle time should be considered when establishing the functional structure of the system and generating the number of work positions and alternatives. In this context, a short cycle time requires the differentiation of the operations. In general, they are carried out on a number of parallel work positions, so that the annual production rate can be fulfilled. This means that the lay-out of the disassembly system will be a parallel lay-out rather than a sequential lay-out, see section 3.4.4. For long cycle times, some operations can be integrated so that the equipment's and operator's idle time is reduced. This requires the introduction of a sequential disassembly lay-out. While considering the possible lay-out in this design stage, the most important thing is to design a system that is able to process the required number of discarded goods. For this purpose, every work position should have a cycle time that is smaller than the calculated cycle time. If this is not the case, measures to increase the capacity of the system should be taken.

During the **conceptual design** phase the functional structure and concept of the optimal disassembly system is generated. As was described before, the overall function and the sub-functions should be established. Then each sub-function should be fulfilled by a proper solution. To achieve a concurrent design of the disassembly process and system, it is recommended that the morphological method be used for the generation of the number of disassembly system concepts, see Figure 6.6.

| Sub-functions | Solutions | | | |
|---|---|---|---|---|
| | | Universal equipment | Programable equipment | Special equipment |
| Unloading of refrigerators | Manual | ● Mechanized Equipment | Robot | — |
| Removing of glass | Manual ● | Mechanized Equipment | Robot | — |
| Removing of cables | Manual | ● Mechanized Equipment | Robot | — |
| Extracting of freon | Manual | — | — | ● Absorption Pump |
| Removing compressor | Manual | Mechanized Equipment ● | Robot | Automated Equipment |
| Breaking down of refrigerators | Manual | Mechanized Equipment | Robot | ● Shredder |
| Processing of PUR | — | — | — | ● Degasing Installation. |
| Separation of ferrous | Manual | — | — | ● Magnetic Band |
| Separation of non-ferrous | Manual | — | — | ● Eddy Current |
| Transportation between the work positions | Manual | Mechanized Equipment | Robot | ● Automated Equipment |

Figure 6.6.: Morphological chart for the generation of the feasible concepts.

The solution principles are combined to create a number of disassembly system concepts. Four disassembly system configurations were generated [Penev, 1993]. The first and second concepts are comparable as they include the same equipment and lay-out. The difference is that the first concept involves an additional back-up work position for the extraction of the freon and oil. The issue is to increase the system's technical availability against additional investment for equipment and an operator. In the third concept, a robotic system for the extraction of the freon and removal of the compressor is introduced. However, the robot can only replace one operator and that makes the investment unprofitable. The fourth concept involves the operations shown in the morphological chart, see Figure 6.6. The discarded goods are processed in a single line, instead of two perpendicular lines, like in the other alternatives. In this way, the transport and handling operations are simplified, resulting in an easy flow of discarded goods.

To select the optimal disassembly system, the generated concepts should be compared and evaluated. To accomplish the evaluation, the designer should establish a number of criteria. In this context, it has to be clear from the start, what the firm's priorities are and what results are to be obtained. In other words, the criteria should be based on the firm's particular requirements. The establishment of criteria can be achieved by interviews with the persons involved or by a quick scan. They formulate the issues that should be accomplished. In this case, the result of the interviews led to the establishment of the following criteria:

- Improved logistics.
- Increase of the total productivity.
- Facilitating worker's operations.
- Achieving a flow production.
- Decreasing inventory.
- Increasing revenues.
- Increasing worker's satisfaction and motivation.

In this case, it was found that alternative 4 represents the optimal system concept. Therefore, it should be considered for further development and implementation.

During the **embodiment design phase**, the number of work positions was arranged according to technical and economic requirements. For instance, in position 1, an extendable conveyor was selected to facilitate the unloading operations. It not only improved the ergonomic conditions but also the efficiency of the operator. Considerations had to be made about the capacity of the conveyor, its size, easy control and maintenance. Similar considerations should be made when selecting the shredder. The designer has to determine the exact capacity of the shredder, space requirements and relationships with the other involved equipment. In other words, every work position should be developed in accordance with the concept and its relationships with the complete disassembly system elements. This design phase ends with the presentation of a definitive layout with all necessary dimensions.

During the **detail design**, the fixture mechanism for the positioning of the refrigerators in the work positions and other particular disassembly tools had to be developed. Most of the disassembly units and tools which were used are the same for assembly, like mechanical screw drivers and transport equipment.

The last phase of the suggested methodology is the **implementation** of the selected disassembly system. This phase was carried out by the company.

### 6.2.4 Description of the developed dismantling system

This section describes the dismantling process developed and the corresponding system. In the new design, see Figure 6.7, the refrigerators are delivered to the first position in containers. Worker 1 unloads the refrigerator using a telescopic extendible conveyor belt located between the containers and the transport conveyor. The worker can reach every refrigerator in the container and put it on the transport conveyor with a minimum of effort. After unloading, the unfixed inner parts (glass, rubber and cables) are removed and put in a container, which can move along the transport conveyor. Finally, the refrigerators are positioned in the required orientation.

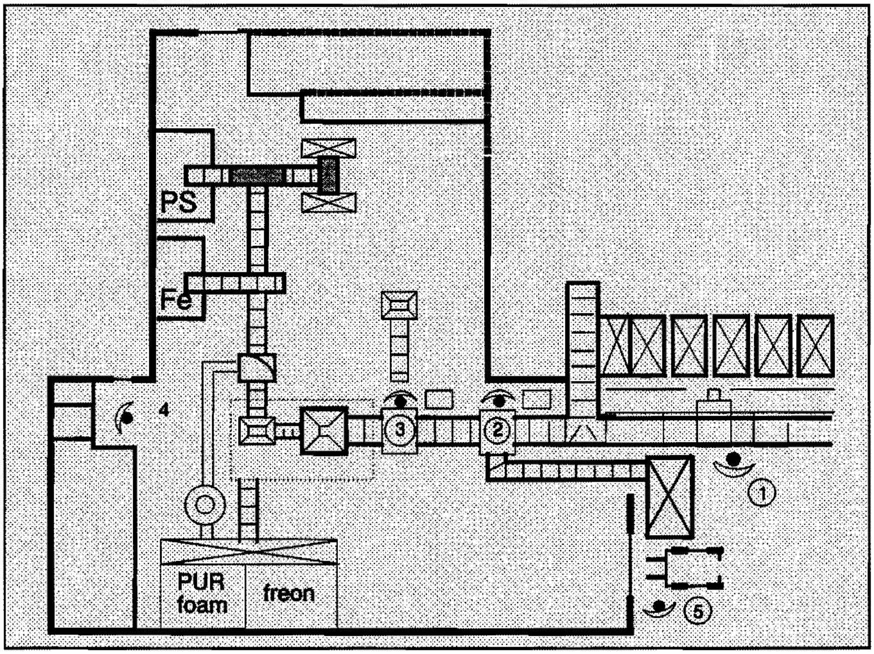



Figure 6.7: Lay-out of the proposed dismantling system.

Before arriving at position two, refrigerators with ammoniac in the cooling system or glass in the insulation layer are passed to a secondary line by means of a pneumatic pusher. For the identification of the product type, product information is required. It can be provided by using an identification label so that the operator can decide what the next destination of the refrigerator will be. When a refrigerator arrives at work position two, it is fixed and the freon and oil are extracted from the compressor. Next, the attachment of the compressor is cut by using a pneumatic cutting device, which speeds up this operation. The compressor falls on a conveyor, which is located under the main line or next to it. This conveyor transports the compressor to a container outside the factory. With the proposed changes, compared to the initial situation, the worker is no longer concerned with handling, positioning and fixing operations, which improves the working conditions.

In position three, if required, the doors are removed and transported to a shredder. Next, the plastic box is taken out and passed to a grinder. Through these actions, two goals are achieved:

- The doors are removed closer to their end destination, which means less internal transport.
- Pure plastic materials are obtained.

In the fourth position, the refrigerators are granulated in a shredding installation. The different materials from the shredder (Fe, Al, Cu, Ps, PUR, etc.) are separated and then transported automatically to their end destination. Various well-known techniques (permanent belt magnets, drum magnets, eddy current, blast air, etc.) are used for the separation of the materials. In addition, the shredder is closed in order to avoid emission of the freon, which is extracted by forced ventilation and transported to the degassing installation.

The fifth position is concerned with the internal transport. The operator should remove filled containers and execute some transport activities. Furthermore, he should support other work positions whenever he is idle. Additional tasks like preventive or on-line maintenance are also included. The workers should be trained to execute every operation within the factory. They should be able to take over each other's task if necessary. In addition, maintenance activities have to be assigned to them.

The proposed design was developed for an yearly production rate of 60,000 refrigerators. The production rate is limited by the capacity of the freon extraction equipment. The rate could be considerably higher if a second parallel work position for the freon extraction was introduced. The capacity of the shredder could be another bottle-neck. It should be chosen with respect to the expected annual production rate and possible changes within the project life cycle. In addition, considerations should be made about external factors that can influence the dismantling process. For this purpose a risk analysis should be carried out [van Bragt, 1992]. The essence of such an analysis is to consider the external factors that influence the introduction of the selected disassembly system. In this case, the following aspects have to be taken into account:

- o Possible changes in recovery technologies and equipment.
- o Variation (±15%) of the number of refrigerators that are offered for processing.
- o Variation (±15%) of the price of secondary materials.

In the near future, the ways to introduce advanced recovery technologies and equipment will be limited because the discarded goods are not recovery friendly. This means that no technology changes are expected which would affect the recovery process considerably. In this context, the developed disassembly system remains the optimal solution. In addition, the suggested disassembly system is developed to fulfil the annual rate that is estimated at about 60,000 [refr./year]. However, the system is still profitable for a recovery rate which differs by ±15% from the required rate. Similar considerations can be made about the change in the price of secondary materials. In has been found that a deviation of ±15% from the expected prices does not alter the selected concept. In other words, it can be concluded that the developed system fulfills all established requirements and can be considered for implementation.

The new system has a number of attractive features and advantages compared to the old design. As can be seen in Figure 6.8, the percentage of the recovered materials, like ferrous, plastics, aluminum, is substantially increased. It is estimated, that the total recovered percentage from the refrigerator's mass is increased from 65% to 95%. In this way the current legislation requirement is fulfilled concerning the recovery of a minimum percentage (70%) from the discarded goods. In addition, the processed freon mass is somewhat increased by the introduction of the shredder installation. These results can be achieved because of the improvements made in the production process and the introduction of the new dismantling system. On top of that, the number of workers is reduced from 15 persons to 6 persons. The investments for equipment result in additional capital costs, but those are compensated by the reduction of labour costs. In effect the total net result and productivity are increased. These data show the benefits of the implemented dismantling system, which is achieved by utilizing the suggested systematic approach.

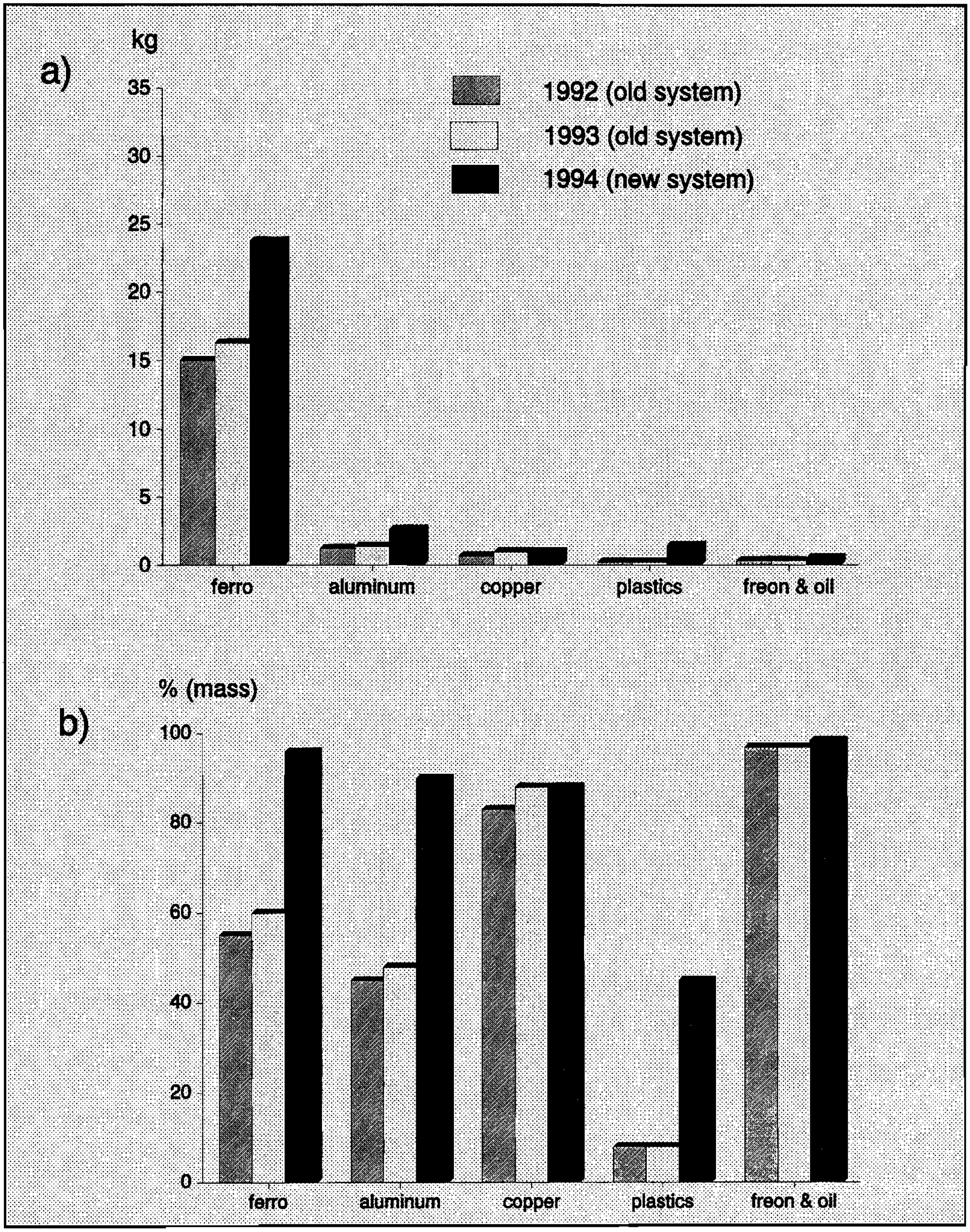



Figure 6.8: a) Absolute mass of recovered materials in kg.
b) Relative percentage of recovered materials per type.

## 6.3. Optimal recovery of consumer electronic goods

### 6.3.1 Introduction

The flow of discarded electronic goods has become tremendous and considerable problems for society are predicted. As was mentioned before, some European governments are introducing various rules that are having an increasing influence upon companies. They are being pushed to take back their goods after usage and to recover them in accordance with the legislation rules. In addition, companies are considering recovery so as to be able to develop strategies for the design and reuse of the next generation of products.

In the Netherlands, a calculation was made concerning the expected amount of electronic products. This calculation was based upon the penetration degree, the average mass and the average life of goods. For the year 1992 it is estimated that 33 kilotons of electronic goods were discarded like:

- o 20 ktons of tv sets.
- o 8.5 ktons of audio equipment.
- o 3 ktons of computers.
- o 1.5 ktons of telephone apparatus.

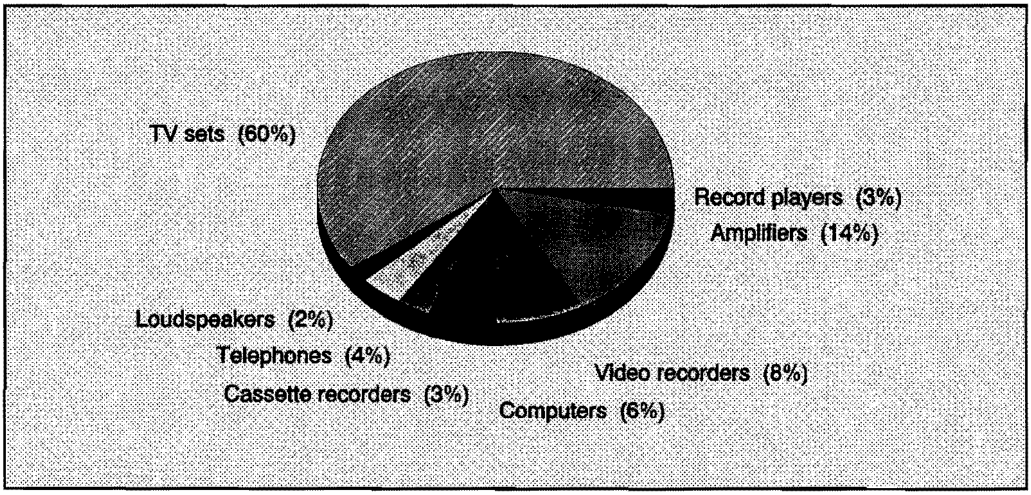



Figure 6.9: Distribution of the mass of discarded electronic goods in the Netherlands [Blonk, 1993].

In addition, Figure 6.9 shows the distribution of the mass of various discarded electronic goods as a percentage of the total flow. From this total, 5 ktons comes from industry. As an indication of growth, it is estimated that the mass will be 57 ktons in 2005. At the moment, the largest part of the discarded electronic products is not yet offered for waste treatment, but is often stored at home. Furthermore, a large quantity of electronic equipment goes to the landfill (8 ktons). Only a fraction is collected separately. In order to reduce the volume of waste and to remove the poisonous materials without leakages to the environment, the Dutch government, among others, is developing and implementing courses of action and tools aimed at stimulating companies to take care of such waste control, including the disassembly and recycling of discarded goods. In this way, it is assumed that the landfill for electronic consumer products may disappear and that a profit can be generated [Blonk, 1993]. For this purpose, a number of disassembly systems have to be developed that are able to process a wide range of discarded electronic goods. This chapter focuses on the development of a disassembly system's concept for the recovery of electronic goods. The design process will be carried out according to the suggested design approach.

### 6.3.2 Collection of market information concerning the recovery of various electronic discarded goods

The design of a disassembly system starts with the collection of **market information**. The aim is to investigate all aspects that influence the recovery of discarded goods. In this context, the legislation is still a main driving force and therefore it should always be considered. Two types of legislation requirements can be distinguished:

- Environmental requirements.
- Recovery requirements.

The *environmental requirements* concern all actions that should be carried out to reduce the impact of discarded goods and to protect the environment. For this purpose, a number of rules are introduced that forbid the storing of chemical and poisonous materials in the landfill. This means that such materials should be processed so that the environmental impact can be reduced to the level required by legislation. At present, legislation does not prohibit the storing of discarded electronic goods. However, some components are regarded as poisonous and their storing costs a lot of money. If such fractions are found in the output flow, the price of the secondary materials obtained is considerably lower. Moreover it is expected that in due course, the storing of electronic equipment will be totally forbidden. These governmental actions push companies to search for solutions to remove the poisonous and chemical fractions in order to fulfil the rules and to avoid high storage taxes. In this context, disassembly is an indispensable process in the accomplishment of aforementioned issues. In many cases, the poisonous fractions and/or components can only be removed safely and in an environmentally friendly way by means of disassembly. Consider, for example, the consequences if capacitors and/or batteries are removed by destructive techniques (dismantling) or are shredded together with the valuable materials. In this way, it is obvious that poisonous fractions can be found in the environment or in the output flow, which diminishes the introduction of a disassembly line. This is one of the reasons *why* disassembly should be applied when recovering discarded electronic goods.

The *recovery requirements* have not yet been introduced by legislation. However, it is expected that in the year 2000, the minimum required recovery percentage of discarded goods has to be 70%. Moreover, the recovery percentage is expected to increase gradually with the introduction of a new generation of products. In this context, it is important to obtain as much experience as possible concerning the disassembly and recovery of discarded goods, which will contribute to the fulfilment of the expected rules. In brief, when considering legislation, the introduction of disassembly systems is regarded as a significant issue that can not be underestimated.

Besides the above, another reason for the recovery of discarded goods are those clients who are interested in purchasing the secondary materials (components) against attractive prices. Therefore, to increase the market share, a recycling company has to offer such materials at prices that are lower than those for raw materials. This is not always an easy task, but with the improvement of the current disassembly processes it can certainly be achieved. Also the prices of raw materials are expected to grow because of shortages of mineral sources and oil, which will make the usage of recycled materials more attractive from an economic viewpoint. Based on the above, it can be concluded that the recovery of discarded electronic goods is justified from various viewpoints. The following step is to determine what parts and materials have to be disassembled and recovered in order to fulfil the legislation rules and to generate profit. For this purpose, the variety of discarded goods should be analyzed that represents the second step from the systematic approach. It is described in the following section.

### 6.3.3 Clarification of the task

During the collection of market information, the reason for the application of disassembly has been defined. The next step is to find out *what* should be disassembled so that the established requirements and goals are achieved. In addition, the business philosophy of the firm, which entails the established traditions in the recycling business, is important to determine *what* should be disassembled. Such a philosophy is based on the customers who are demanding what the purity of the recovered materials should be and what quality standards the recovered components should fulfil. In other words, this aspect influences the determination of the disassembly strategy and thus the design of the corresponding system. In this case, the background of the firm is related to the recycling of a huge volume of discarded materials. Moreover, there are a number of customers who are willing to purchase recovered materials with a high purity percentage. Therefore, the aim of the company is to generate pure secondary materials from the discarded electronic goods to satisfy customers' requirements and to keep the already established business tradition in the recycling branch. Taking the aforementioned into account, the exact determination of *what* should be disassembled is accomplished during the **clarification of the task**. The core of this stage is to analyze the discarded goods with respect to the determination of the disassembly strategy. The analysis process includes considerations concerning the discarded goods' assortment, structure and composition. A clarification should be given what components and materials have to be recovered and/or removed. In general, electronic goods consist of the following fractions:

- Ferrous.
- Non-ferrous.
- Pure plastics.
- Mixed plastics.
- Clean circuit boards.
- Poisonous circuit boards.
- Electrical motors.
- Transformers.
- Coils.
- Glass.
- Others.

It is of importance to determine which components or materials should be considered poisonous in order to generate the number of compulsory disassembly steps. Such materials can be found in some sub-assemblies. The most important poisonous materials are batteries, plastics that contain flame decelerators with bromine and capacitors with PCB (Polychlorinated Biphenyl). Since 1983, the production of PCB capacitors has been forbidden [Bauer, 1988]. If the percentage of poisonous materials in the output flow is bigger than the legislation norms, the output flow is regarded as chemical waste. It can not be stored in the landfill and should be processed according to the established rules, which costs a lot of money. Therefore, the best approach is to apply disassembly to remove the poisonous materials so that the disposal costs can be reduced and the revenues of the output flow can be increased. Moreover, it is expected that the governmental rules will become more severe and in a due course new rules will be introduced for the complete processing of discarded electronic goods. This implies that by applying disassembly, higher profits can be generated from the recycled materials while fulfilling the legislation rules.

There are several options we can consider with disassembly. The discarded electronic goods may be reused again after reparation and testing (service). This option only seems to be feasible for goods that are produced by the same firm. For instance, Siemens-Nixdorf is collecting their own discarded electronic goods and sells them after reparation to a secondary market. It is also possible to reuse some components, like IC's for game computers. Generally, reuse of components is hardly applied as there is no market for second-hand components of electronic apparatus [Angerer, 1993]. Even Siemens-Nixdorf intends to reduce the activities related to the reuse of apparatus and components because they are not economically justified. In addition, some producers of electronic equipment do not allow the reuse of their components for commercial purposes by other firms. Thus, it can be concluded that the most important issue involved with the recovery of discarded electronic goods is the recycling of materials and decreasing the disposal costs. This means that the goods should be processed so that pure material fractions can be obtained. In other words the disassembly strategy should be concerned with:

- Removing the poisonous components by means of disassembly.
- Generating pure material fractions with a high profit.

Generally, most of the poisonous parts, like batteries and capacitors, can be found in circuit boards while poisonous materials, like lead, cadmium, zinc chrome and phosphorus, are part of tv tubes and monitors. On the other hand, the discarded electronic goods consist of a number of materials, like ferrous, plastics, glass, copper and aluminum, that can be recovered. The reuse of ferrous and non-ferrous is economically feasible at present. The developed technologies allow the separation of ferrous and non-ferrous from the other fractions by means of magnetic and Eddy current techniques. However, the mechanical separation of various plastics is a difficult or even impossible task; therefore they should be separated by means of disassembly before shredding. After regaining these valuable materials, the remaining fraction should be treated as waste. Based on this analysis, the disassembly strategy can be established.

### 6.3.4 Determination of the disassembly strategy for the recovery of some discarded electronic goods

The determination of the disassembly strategy has been defined as the core of the suggested systematic approach. It gives the optimal disassembly operations and level by which the established goals can be achieved.

This section emphasizes the determination of the disassembly strategy for tv sets as they represent the largest part of the discarded electronic goods. In addition, a tv set is a complex product and consists of parts and materials that can be found in a wide range of electronic goods. For instance, the tube can also be found in monitors. In addition, circuit boards are also part of computers, radio receivers, tape recorders, video recorders, telephones and amplifiers.

First, the disassembly strategy has to be determined for the removal of the poisonous materials. For this purpose, a general model of a tv set is used. Such a model includes the most important sub-assemblies and parts involved in the disassembly strategy. In general, a tv set can be represented by the following sub-assemblies: case (1), tube (2), circuit board (3), loudspeaker (4) and others (5), see Figure 6.10. As was mentioned before, poisonous materials can be found in the tube and circuit board. This means that these sub-assemblies should be removed in the most economic way in order to fulfil the legislation rules. This implies a minimum number of disassembly operations that have to be carried out. As was explained before, the disassembly alternatives can be generated by an AND/OR graph, see Figure 6.10. Next, we have to determine the profits of every recovery step. In the figure, the profits are given by $P_1$, $P_2$, etc. Finally, the optimal disassembly sequence is determined by comparing the total profits obtained from the disassembly plans generated. It is found, that the optimal disassembly plan includes the following operations:

1) Disassembly of the case (profit $P_1$).
2) Disassembly of the tube (profit $P_{2,1}$).
3) Disassembly of others (profit $P_{3,2}$).
4) Disassembly of circuit boards (profit $P_4$).

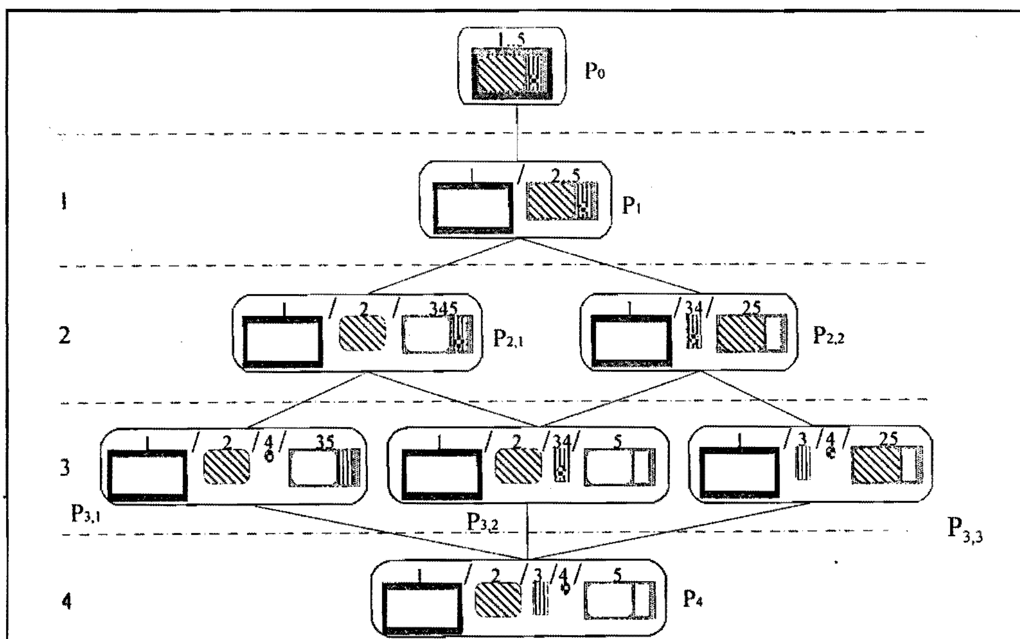



Figure 6.10: Simplified disassembly plan for the recovery of a tv set.

After accomplishing these operations, disassembly should be terminated because it does not contribute to the fulfilment of the established rules or generation of higher profit. The recovery of the remaining fractions is achieved by shredding and separation. In practice,

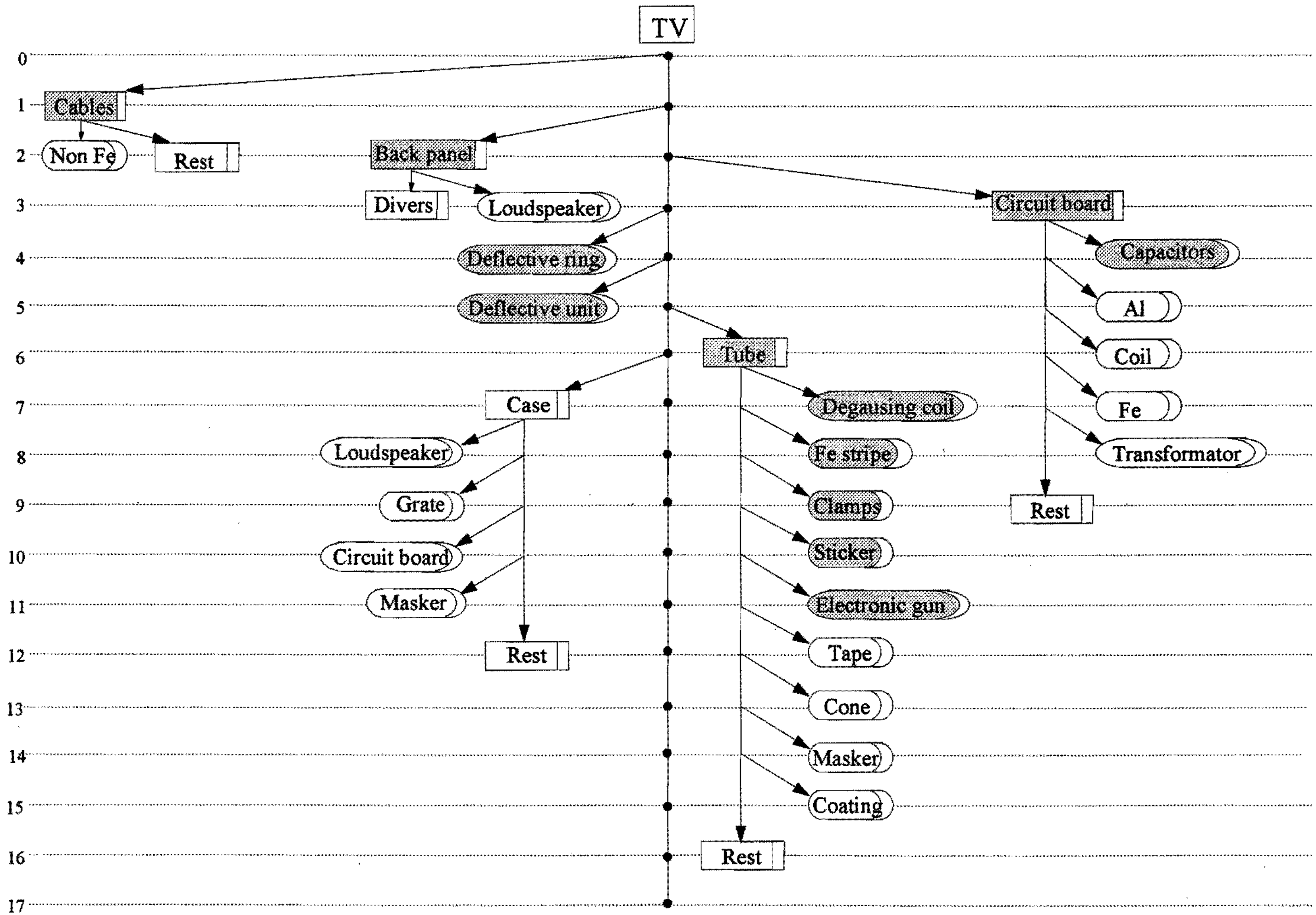



Figure 6.11: Disassembly graph for a TV.

the disassembly and recovery of a tv set is rather complicated, because it consists of a huge number of components and materials. In other words, the disassembly plan for the recovery of a tv set is more complicated than that represented in Figure 6.10. However, it can be simplified by restrictions imposed by the structure of the discarded electronic goods or by technical requirements. This results in the generation of the disassembly plan given in Figure 6.11, which is used for the determination of the optimal disassembly depth. To accomplish this task, the profit of every disassembly operation has to be calculated. The results obtained can be represented in a diagram as shown in Figure 6.12. It can be seen in what step the disassembly curve reaches the maximum level, which implies the generation of the highest profit. However, the optimal depth is not only based on the maximum profit one can obtain, but also on the fulfilment of legislation requirements.

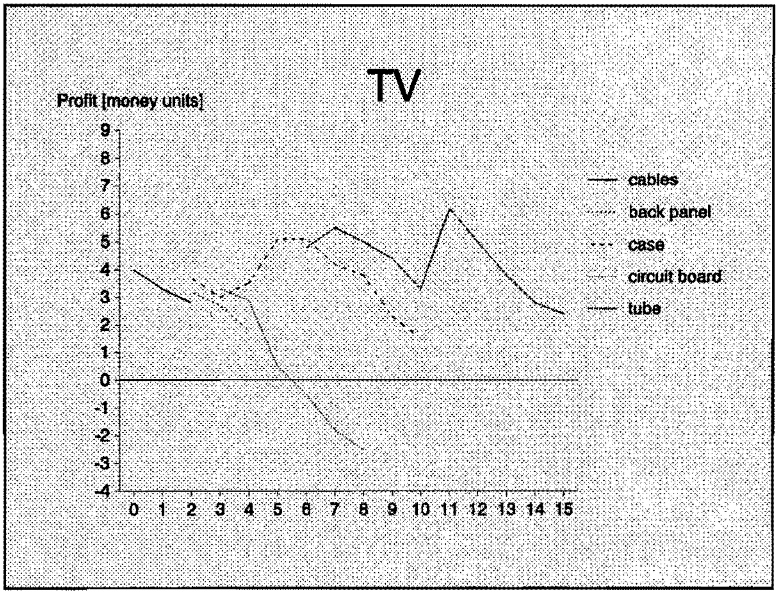



Figure 6.12: Profit curve of a tv set.

In this case, a number of tv sets has been investigated, which were produced in the period between 1977 and 1993. The obtained results are similar to those given in the figure. It shows that the maximum profit is obtained with the completion of the eleventh disassembly step. In addition, the figure gives the optimal disassembly level of every sub-assembly or component. For instance, it can be seen that the maximum profit for the cables is generated in the first disassembly step; further disassembly of this sub-assembly is not profitable. In this way, the optimal disassembly level for every sub-assembly can be determined from the figure. This results in the following disassembly steps that represent the optimal disassembly level and sequences:

1) Removal of cables.

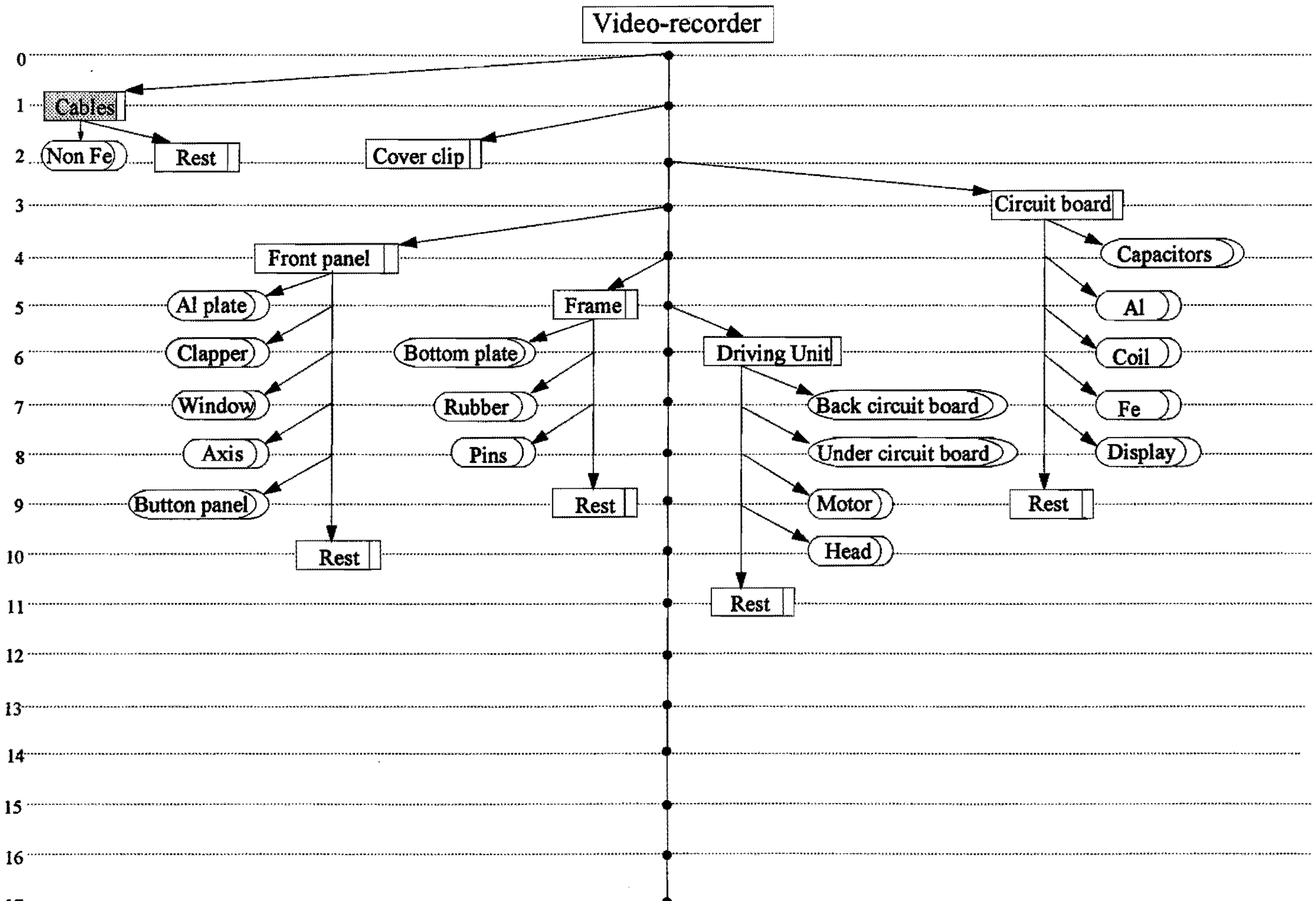



Figure 6.13: Disassembly graph for a video-recorder.

2) Removal of back panel.
3) Separation of the tube from the tv set's case.
4) Disassembly of the circuit board and removal of capacitors.
5) Disassembly of the deflection unit's ring.
6) Disassembly of the deflection unit.
7) Dismantling of the degaussing coil.
8) Dismantling of the ferrous stripe.
9) Removal of clamps.
10) Removal of stickers.
11) Removal of the electronic gun.

The above strategy implies that the tube should be disassembled until the electronic gun is removed; in Figure 6.11 this is illustrated by the shaded box at step 11. By accomplishing this process, the percentage of the recovered materials is estimated to be higher than 70% thus fulfilling the legislation requirements. In addition, by the separation of the poisonous materials, the environmental issue is dealt with too while a profit from the recovery process is generated .

In the same way, the optimal disassembly plans for the recovery of monitors and video recorders can be determined. The disassembly of a monitor can be compared with the disassembly of a tv set, as most of their sub-assemblies and components are similar. Concerning the disassembly of a video recorder, the disassembly plan represented in Figure 6.13 gives the optimal disassembly sequence, which is based on the obtained profits represented in Figure 6.14.

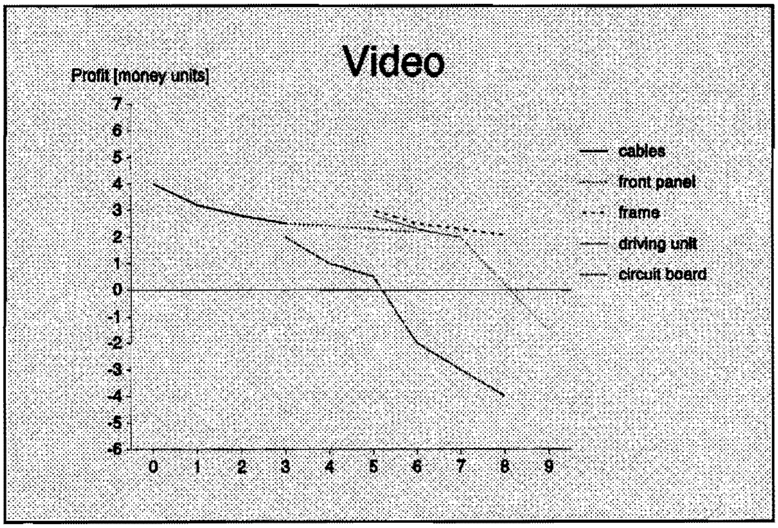



Figure 6.14: Recovery profits of video recorder.

In addition, it is found that from an economic viewpoint only the removal of cables is justified, because it generates the highest profit. The decreasing profit curves after this step imply unprofitable operations. However, disassembly should also be applied for the removal of the capacitors, which ties in with the environmental issue. Because of these requirements, disassembly steps 2 and 3 should also be carried out to get access to the capacitors. Further disassembly is not profitable and the remaining fractions are sent to a shredder. By shredding and separating materials, the minimum required recovery percentage (70%) is achieved. In other words, the optimal disassembly plan consists of the following operations:

1) Removal of cables.
2) Disassembly of the head cup.
3) Removal of circuit boards.
4) Removal of capacitors.

With the accomplishment of these operations, the legislation rules are fulfilled concerning the minimum recovery percentage and environmentally friendly processing of the available poisonous fractions (capacitors). Based on the optimal disassembly plans of various discarded electronic goods, a general disassembly system for their processing can be developed. It should be able to handle all operations that are required for the recovery of a wide range of discarded electronic goods. For this purpose, similar disassembly operations have to be integrated and executed in common work positions. With this in mind, a rough concept of a disassembly system has been developed, see Figure 6.15.

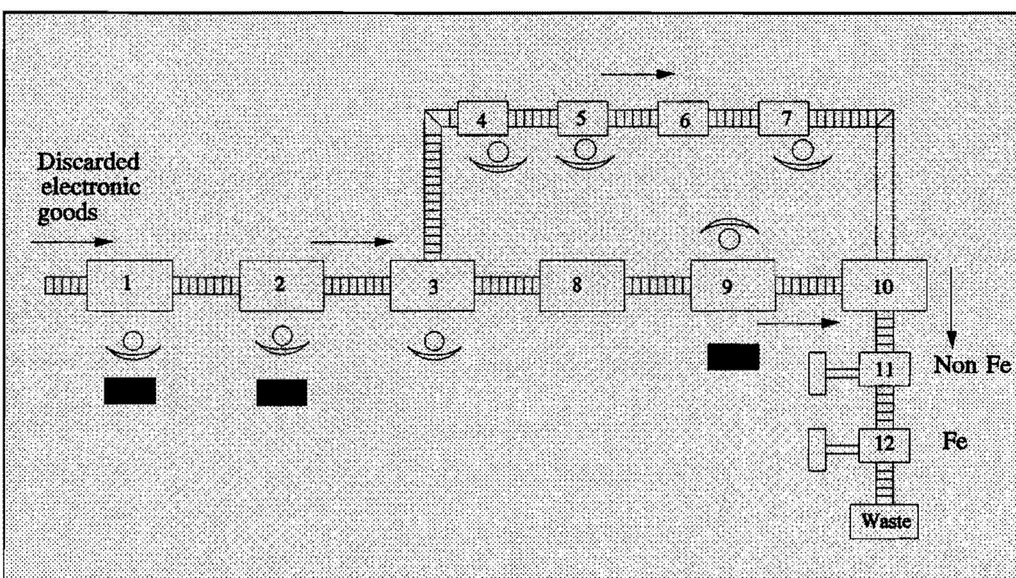



Figure 6.15: A disassembly system concept for various electronic goods.

In position 1 and 2, the cables and cases of all discarded electronic goods are dismantled. The cables are sold and the cases are treated as waste. Position 3 represents the disassembly of the tube from tv sets and monitors. Position 4 is the beginning of a line for the disassembly of the tube. Then the disassembly follows of the deflection unit's ring and the removal of the deflection unit (pos. 5). At position 6, the degaussing coil, ferrous stripe and clamps are removed. The last disassembly step according to the determined strategy includes the removal of the stickers and the electronic gun, which is accomplished at position 7. Then the remaining fractions are passed to a shredder (pos. 10). Position 3 can also be regarded as the beginning of a second parallel disassembly line. At position 8, the circuit boards are removed. Next, we have the removal of capacitors (pos. 9), if it is required. The remaining fractions are sent to a shredder after which the mixed flow generated is divided into a number of material fractions by means of separation techniques, as has been explained already. The generated material fractions are transported by means of conveyors in the corresponding containers, as the pure fractions are separated from chemical and other waste.

The described concept can be implemented by a recycling company that is interested in the recovery of electronic goods. However, particular aspects, like new technologies, space requirements, budget, number of discarded goods, available clients and market prices, should be considered. In this context, tv tubes can be recovered not only by manual disassembly but also by means of modern recovery processes [Ebach, 1993], like:

a) Mechanical: the cone is separated from the screen by sawing.
b) Thermal: the separation of the screen is achieved by melting the glass soldered joint.
c) Glass-related: slitting and cracking of the tube.

These recovery methods are mostly applied by specialized processing companies. This can be explained by the high investment that is necessary to introduce such systems. They may be profitable if a high quantity of discarded tubes are offered for processing. This is the reason that the manual dismantling of tubes is still a feasible option. It should be considered together with the new technologies, so that an optimal disassembly system can be developed.

## 6.4 The design of a disassembly system for consumer electronic goods and household appliances

### 6.4.1 Introduction

Nowadays, a wide range of discarded goods is offered for processing in a random order. The recycling companies face a difficult task if they want to disassemble and recover goods that have diverse components, shape and composition. In order to solve this problem and to increase the market share, a company should introduce a disassembly system, that has to be able to recover various discarded goods. This task can be accomplished by the application of the suggested systematic approach. In this context, the present chapter describes its application for the development of a disassembly system for the integral recovery of a wide range of household appliances and electronic goods.

### 6.4.2 Systematic design of a disassembly system for various discarded goods

The design of a disassembly system for the recycling of discarded electronic goods and household appliances should be carried out according to the suggested systematic approach. As already described, the process starts with the collection of **market information**. In this case, the same considerations and conclusions are valid as those described in section 6.2 and 6.3. In brief, the recovery of discarded household appliances and electronic goods is justified from an economical viewpoint and is implicitly required by legislation.

The following step is the **clarification of the task**, which concerns the analysis of the expected mixed flow of discarded goods. This requires their classification in groups concerning their quantity, diversity and composition. The aim is to make possible the processing of these goods by a general disassembly system. In this context, the following main groups can be distinguished:

- o Household appliances using freon as a coolant (refrigerators, freezers, etc.).
- o Large household appliances (washing machines, dish washers and boilers).
- o Small household appliances (coffee makers, irons, shaving equipment, etc.).
- o Consumer electronic goods with tubes (tv sets and monitors).
- o Other consumer electronic goods (tape recorders, videos, cd-players, etc.).

The determination of the disassembly strategy for the recovery of household appliances using freon and various consumer electronic goods has been described in the previous sections of this chapter. Therefore, this section emphasizes the determination of an optimal disassembly plan for large household appliances. They are complex goods and their recovery results in a number of disassembly steps that should be considered. For instance, consider the recovery of a washing machine. In general, it consists of the following sub-assemblies (components), see Figure 6.16:

- Cables (not shown in the figure).
- Cover panel (E).
- Case (B).
- Integrated plug connection (A).
- Basic element (F).
- Shock absorbers (C).
- Concrete block (not shown in the figure).

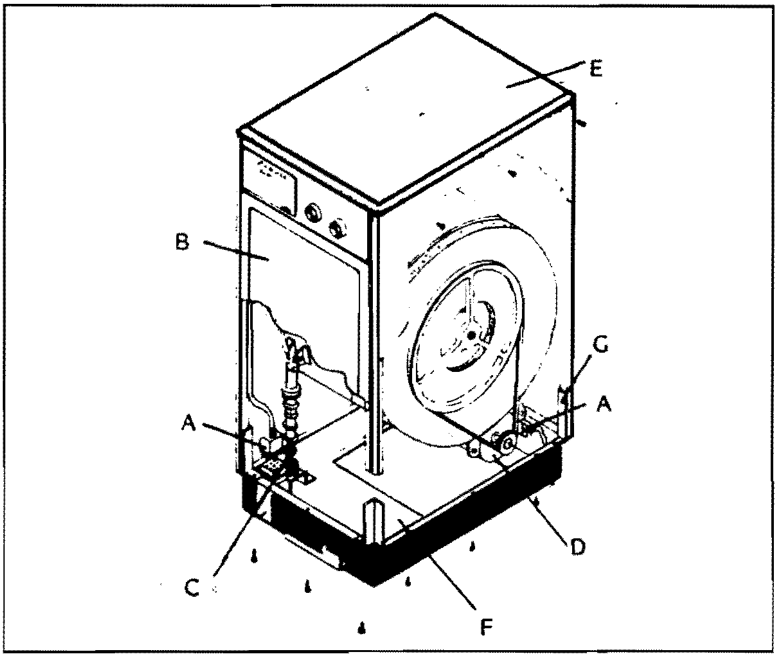



Figure 6.16: Cross section of a washing machine.

In addition, each of these sub-assemblies includes a number of components. This makes the generation of all disassembly alternatives an extremely difficult task. However, it can be simplified by determining what disassembly operations have to be carried out in order to fulfil the legislation rules and to generate the desired output flow. In this case, it is necessary to remove the capacitors in order to obtain pure material fractions and to avoid high storing taxes. In addition, the concrete block and electrical motor can not be shredded, therefore they have to be disassembled as well. Based on the above, the number of disassembly alternatives can be generated. By applying the method for the

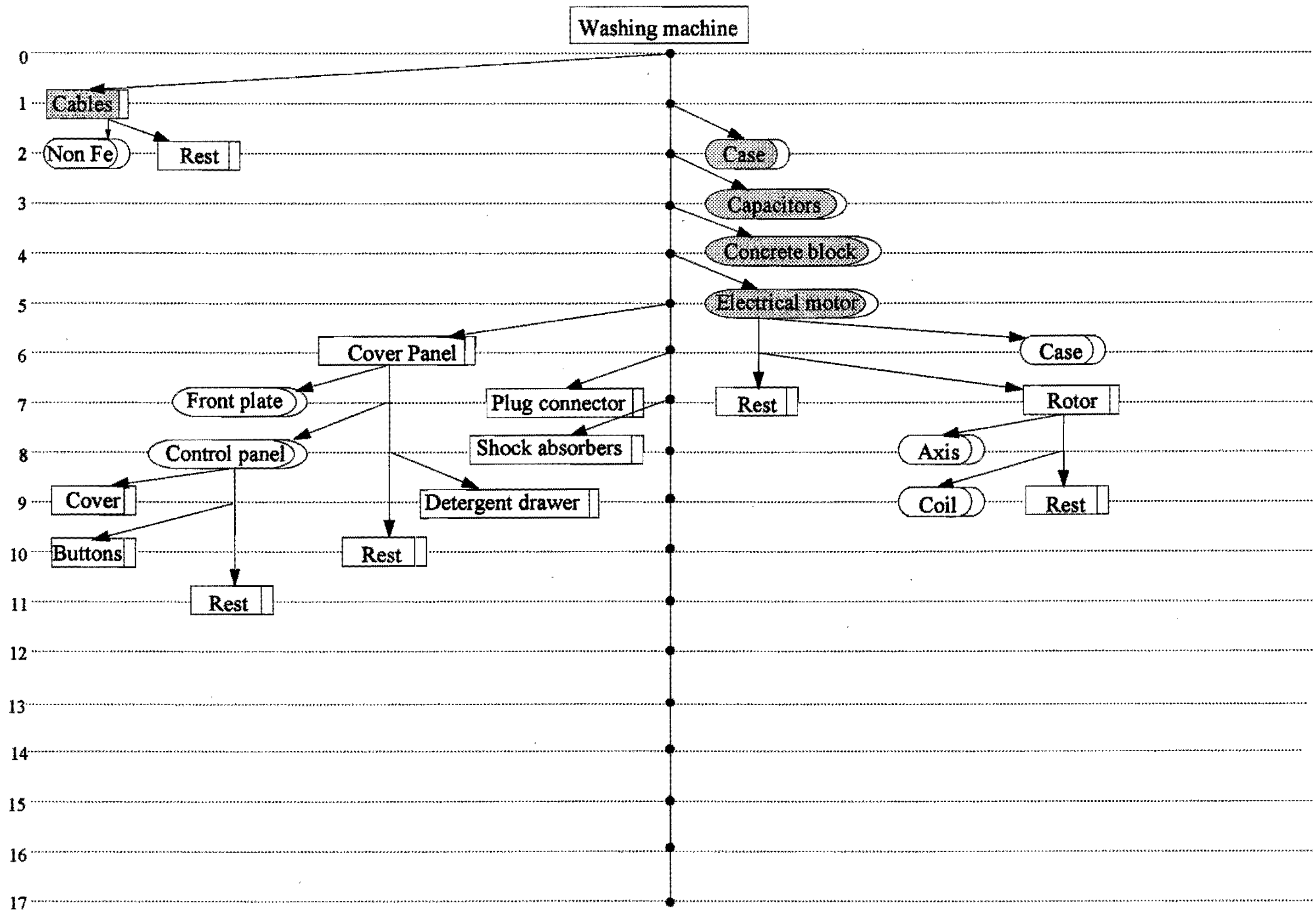



Figure 6.17: Disassembly graph for a washing machine.

determination of the disassembly strategy, the optimal disassembly plan has been determined, see Figure 6.17. It includes the optimal disassembly sequences and depth, which is given by shaded boxes. As can be seen from the figure, five disassembly operations are required before shredding. In other words, the optimal disassembly strategy consists of the following activities:

1) Removing of cables.
2) Removing of a part from the case in order to get access to the other parts.
3) Removing of capacitors.
4) Removing of concrete blocks.
5) Removing of electrical motors.
6) Shredding of the remaining part of the washing machine.
7) Separation of the mixed material flow generated after shredding.

The execution of the above disassembly strategy results in the fulfilment of the legislation rules and generates the desired output flow expressed in money value. In addition, the optimal way to recover other large household appliances is determined, which can be compared to the washing machine described above. Then the generated optimal disassembly plans of various goods have to be integrated into a general plan for the recovery of all large household appliances. It is clear that some operations can be combined and executed in common work positions and that other ones will require particular solutions. In other words, a general disassembly plan should be established where the optimal disassembly sequences and number of operations are represented. Besides the determination of the disassembly plan, it is necessary to consider the activities that have to be carried out in other companies. Based on the number of disassembly plans and the requirements for the processing of discarded goods outside of the company, a complete plan for the recovery of discarded electronic and household goods can be established, see Figure 6.18. It represents all activities that have to be executed in order to accomplish the recovery process.

Before continuing with the design of the corresponding disassembly system, the required cycle times have to be calculated. When a complex disassembly system has to be developed, the cycle times of every specific product group should be determined. The total number of discarded goods, which should be processed in the factory, is estimated at about 225,000 goods a year. They are split into three categories according to their complexity, size and requirements for disassembly. This results in the following sub-flows, which should be disassembled separately:

- o Consumer electronics and small household appliances - 100,000 [goods/year].
- o Large household appliances without freon - 53,000 [goods/year].
- o Large household appliances with freon - 72,000 [goods/year].

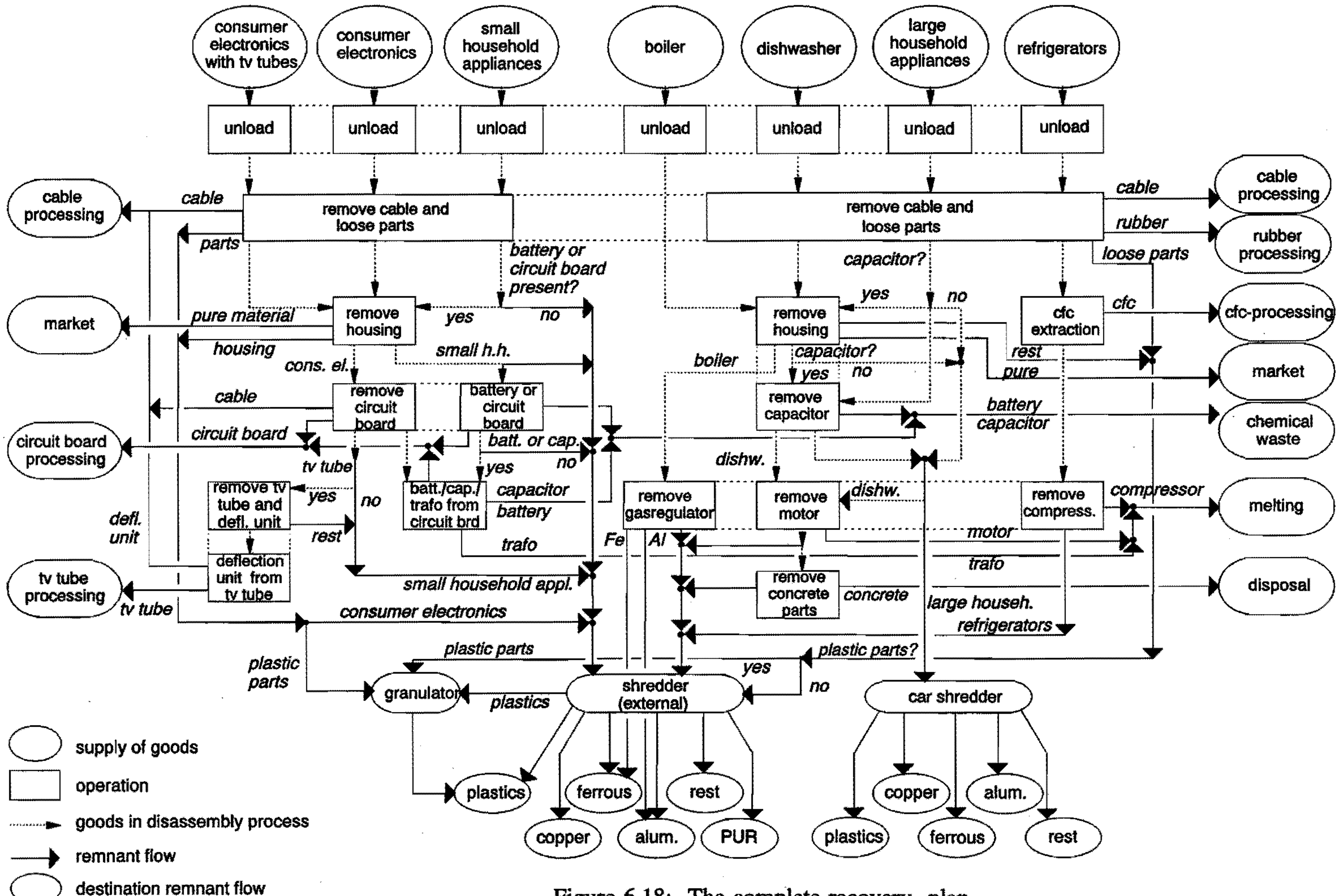



Figure 6.18: The complete recovery plan.

After substitutions in equation (5-1), the cycle times for the flows are obtained as $t_1$=57, $t_2$=107 [sec] and $t_2$=107 [sec]. These cycle times should be considered when developing the disassembly system. It is clear that the duration of a disassembly operation must not be longer than the required cycle time. If this is the case, the operation should be executed on a number of work stations so that the annual rate can always be completed.

Considering the results obtained from the clarification of the task, the designer can continue with the development of the number of feasible disassembly system **concepts (conceptual design phase)**. The required disassembly steps can be found in the general recovery plan, see Figure 6.18. Every disassembly and transport operation represents a system function that should be met by a proper technical solution. In this case the number of functions can be divided into the following:

- Unloading of the discarded goods from containers.
- Disassembly of large household appliances.
- Disassembly of refrigerators.
- Disassembly of consumer electronics and small household appliances.
- Shredding.
- Separation of various material fractions.

By using the morphological method, five competitive concepts were created [Reynders, 1995]. The main differences between them are related to the internal logistics, transport and system lay-out, while the technical equipment and number of operators are comparable. Concept 2 and 4 are based on the existing disassembly system, which is extended with a line for the processing of discarded electronic goods. The other alternatives represent completely new lay-outs of disassembly systems. The processing of the mixed flow of discarded goods is carried out on separate lines according to their type and specific requirements. In this case, the experience obtained by the design of a disassembly line for refrigerators, described in section 6.2, shows that the introduction of robotic systems or other advanced equipment is not profitable at present. Therefore, alternatives with such equipment are not considered. The concepts developed should be compared and the best one should be chosen based on a number of criteria that are specified by the firm. In this case the criteria are listed in a matrix and compared with each other to determine which one has the highest priority, see Appendix 6.3. The following technical (1 to 4) and social (5 to 7) criteria were considered significant by the firm and selected to compare the number of concepts:

1) Flexibility with regard to quantity of product and changes in the lay-out.
2) Easy maintenance.
3) Total productivity.
4) Easy handling and piece flow production.
5) Possibility for communication between operators.
6) Change in work intensity.

7) Safety and ergonomic conditions.

The obtained results from the evaluation are used to select the most feasible disassembly system, see Appendix 6.3. For the final selection these results are represented together with the necessary investment in a diagram, see Figure 6.19.

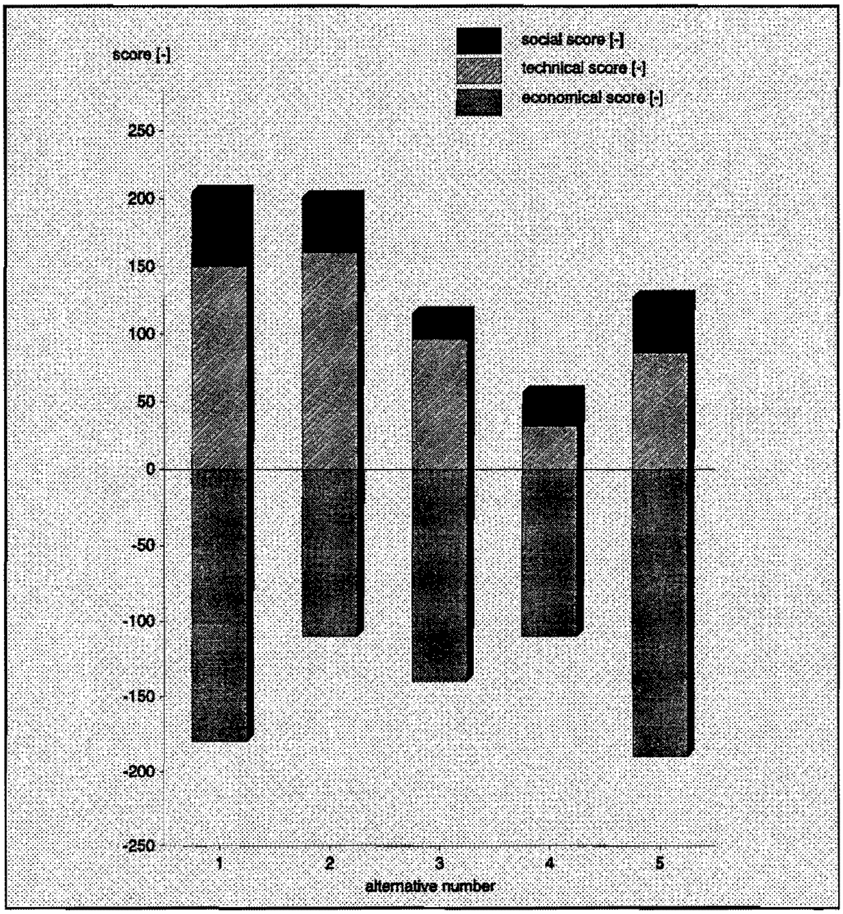



Figure 6.19: Comparrison of concepts.

In this case, because of confidential considerations, the actual investments are replaced by the corresponding economic scores. As can be seen, the first alternative fulfils at most the technical and social requirements. However, the required investment (represented by the economic score) needed to implement the corresponding disassembly systems is considerably higher than that of the second alternative, which also has a high score. In general, to evaluate technical and social criteria against economic criteria, a weighting factor can be assigned to them. In this way, it becomes clear which of them receives the highest priority. This consideration is not involved in the described method that makes its applicability less objective. This is the reason that the evaluation was carried out with weight factors as well. The highest weight factor was given to the economic criterion, which in this case was considered the most important by the firm. The result is that alternative 2 gets the highest total score. It has a relatively high score both for technical and social criteria, related to a relatively low investment level (economic score). In addition, it is emphasized that the same time for the return of investments for all concepts had been considered. Based on the above, the second concept is the basis for the development of the corresponding disassembly system.

According to the selected concept, the definitive lay-out was presented during the **embodiment design**. Finally, the details were worked out and the design of the disassembly systems was completed **(detail design)**. The disassembly system was implemented by the company according to the suggested concept.

In the new design, the discarded goods are delivered in containers and unloaded by means of a telescopic, extendable conveyor, see Figure 6.20.

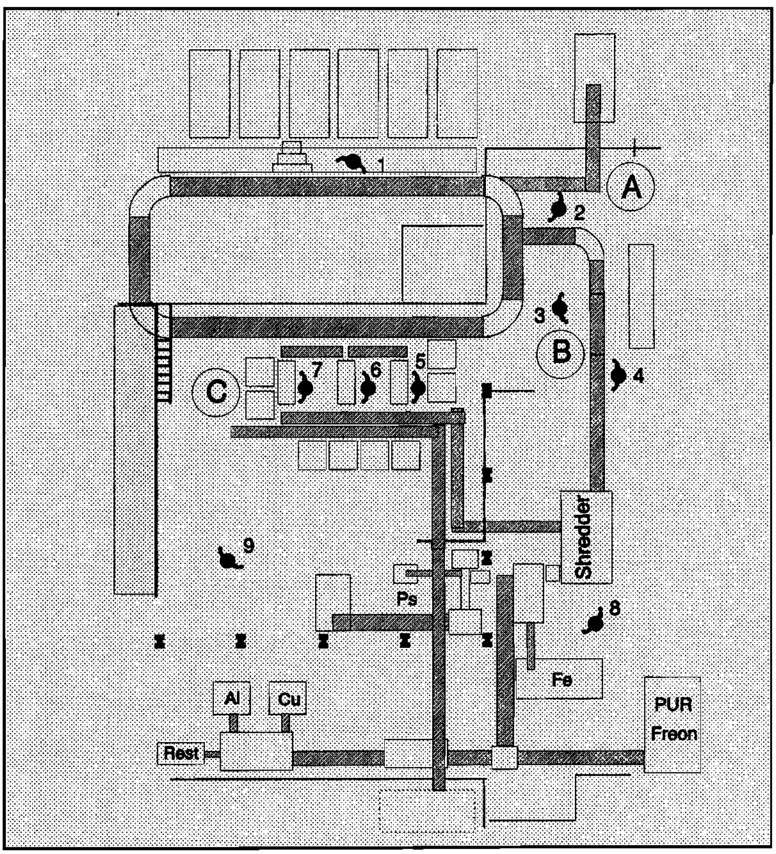



Figure 6.20: The lay-out of the selected concept.

In the first position, an operator removes the loose parts and cables according to the process plan. Then the goods are passed to the carousel conveyor and distributed to three sub-disassembly areas. In this context, the main flow is split into the following sub-flows:

- Large household appliances: they are sent to a car shredder because of technical and economic considerations (area A).
- Refrigerators (appliances with freon): they are transferred to area B.
- Consumer electronic and small household appliances: they are transferred to area C.

The carousel conveyor can be considered as a buffer. If for any reason one of the disassembly areas can not accept more goods, they will remain on the conveyor (which runs with constant speed) thus making a number of rotations necessary before it is possible to pass them on to the following work positions.

At position 2, the poisonous components (materials) of the large household appliances are removed. For instance, capacitors of washing machines are disassembled to obtain purer fractions after shredding. After this operation, the goods are passed to a container and transported to the car shredder, which can process goods with a bigger dimensions.

Position 3 and 4 represent the disassembly area B. There the freon and the compressor are removed from the refrigerators by means of mechanized equipment. Also the gas regulator from boilers and the electrical motor from dishwashers are disassembled. Then the goods are transported to a shredder. Later, the PUR is separated from the material flow and transported to the degassing installation. The dismantling process related to refrigerators is the same as described in Section 6.2.

The third sub-flow of discarded goods is distributed to the disassembly area C. This represents a line for the dismantling of consumer and small household appliances. It consists of three work positions. In position 5, the cases are dismantled and put in the corresponding containers. Then the goods are moved to work position 6, where the circuit boards are removed. The line ends with position 7 where the tv tubes are dismantled and put in containers. The material fractions left over after all the dismantling operations are separated in containers or passed to the shredder by means of a conveyor. In the shredder, the remaining materials from the areas B and C are broken down and separated by means of well-known techniques, as described earlier.

Position 8 represents an operator who is responsible for the shredder and degassing installation, while number 9 is engaged with the internal transport. It should be mentioned, that the operators have flexible work orders due to the wide variety of discarded goods. They should be able to carry out all operations required for the efficient processing of the discarded goods. If the annual production rate has to be increased, the disassembly line C can be extended with a number of work positions. In the figure one can see, that there is enough space to accomplish this task if necessary. In addition, all operations (handling, disassembly, etc.) are mechanized or automated depending on the current restrictions and requirements concerning the fixed flow of discarded goods.

The suggested disassembly system concept includes the same advantages obtained from the implementation of the dismantling line for refrigerators. Moreover, by using the systematic approach new aspects are considered and worked out in the early design phase, so that most disadvantages and problems associated with the old design are avoided or solved. In this context, a comprehensive plan for the complete recycling of all discarded goods is established, which results in clear process planning. In this case, the disassembly strategy for the recovery of discarded electronic goods is different from that described in Section 6.3. This can be explained with the specific business philosophy of the two firms. In this context, the disassembly strategy is influenced by existing clients who have different requirements concerning the purity of the recovered materials. In addition, important aspects, like the mass of the processed discarded goods per year, market prices and logistics additionally influence the disassembly strategy of a firm. Taking into account these specific aspects, the designer can carry out the design process in a systematic way, as no important step is omitted. In this way, the most feasible disassembly system concept can be developed for the current specific requirements and constraints imposed by the fixed input flow (discarded goods). The result is the fulfilment of the established goals concerning the generation of the desired output flow and legislation requirements.

## 6.5 Some product design considerations for an easy disassembly and recovery

There is no doubt that the design of recovery friendly products is a significant issue nowadays. In this context, the products should be considered from a life cycle viewpoint and designed according to a concurrent design approach, to satisfy the requirements concerning their production, usage, reuse and disposal. For this purpose, new design rules should be developed which will facilitate the entire design process. According to the suggested product life cycle model in Figure 5.2, new design rules should be developed on the basis of the obtained experiences during the recovery of various discarded goods. In this way, the hidden disassembly difficulties become transparent and can be solved during the conceptual design of new products. These design guidelines can be regarded as complementary to an integral design approach for the development of sustainable products, as was described in the previous chapters. However, reliable and complete guidelines for the design of recovery friendly products can only be created if the current discarded goods are considered comprehensively from a life cycle viewpoint. Such guidelines add new requirements to a product design. Some of them will be similar to existing ones, but it is evident that new guidelines will be developed too. The new design methods should provide a systematic procedure for the analysis of proposed designs from the perspective of manufacturing, assembly, service, disassembly, dismantling, recycling and disposal. All these aspects have an important effect on various stages of the product life cycle. They should be considered simultaneously in the early stage of a product design. For this purpose, the efforts of various specialists are not only required for the development of such design methods, but also for their proper application in practice.

Regarding the above, this section describes some design considerations and guidelines for the development of disassembly and recovery-friendly household and electronic products. The suggested design guidelines are linked to the difficulties that have been experienced during the recovery of these goods. The aim is to provide sufficient information for the designers who will be involved in the development of recovery friendly products so that the initial disassembly problems can be avoided.

### 6.5.1 Design considerations for refrigerators

The experiences gained with the implementation of the disassembly line for refrigerators (section 6.2) showed that further improvements in the disassembly facilities are hardly possible if the refrigerator's design is not changed. This means that during the design of new products all aspects of the product life cycle have to be considered to create a recovery-friendly refrigerator. A contribution to the development of such guidelines is made in this section.

During the recovery of refrigerators various difficulties have been observed. In the first place the processing of the freon and PUR is very expensive. In order to reduce the environmental impact and recovery costs, another compatible coolant agent has to be found. Besides that, the replacement of freon is a requirement that has already been imposed by legislation. In this context, the usage of this coolant in new refrigerators has been prohibited in the European Community since 1995 [VROM, 1992]. Designers should also avoid the application of disassembly unfriendly joints, if the corresponding sub-assemblies have to be removed by non-destructive techniques. In addition, the number of non-compatible materials should be replaced, because they are difficult to separate and at the end of the process impure material fractions are usually obtained. This either causes high separation costs or lower revenues. For the same reason, the PUR insulation material should also be replaced because part of it always remains in the obtained fractions, which decreases the material revenues. Another important problem, identified during the dismantling of refrigerators, is the position and the attachment of the compressor. This component is recognized to be a valuable component, which means that it has to be disassembled before the product is sent to a shredder. The compressor contains valuable materials and may also be reused as a secondary product. These conclusions justify all the efforts that should be spent to make the disassembly of the compressor easy, cheap and efficient. At present, the automation of this disassembly operation is not profitable because the compressors are attached to a refrigerator by means of various techniques and at different locations; this causes enormous problems during disassembly. These disadvantages have to be resolved in order to facilitate this important and demanding disassembly operation, especially if the option for automatic disassembly is also being considered. In this context, the observed problems can be split up into two main groups and formulated as follows:

- o Problems associated with the used parts (components):
  - The sandwich construction with the PUR foam has high dismantling costs.
  - The attachment of the compressor causes enormous problems during dismantling.
  - The variety of disassembly unfriendly joint techniques causes longer disassembly times and higher costs.
- o Problems associated with the used materials:
  - The use of freon as a coolant and for the production of isolation material.
  - The usage of a variety of plastics which results in:
    - Difficult identification.
    - Difficult separation.
    - Low percentage of recyclable materials.
  - The PUR foam that is difficult to separate from the other materials resulting in impure material fractions and low revenues.
  - The Formica table-top is not recyclable.

Based on the above, some guidelines for the design of refrigerators have been developed to support designers who are developing new products, see Table 1.

To verify the applicability of these guidelines, a project has been carried out concerning the design of a disassembly and recovery-friendly refrigerator [Pauw, 1994]. In the suggested concept, the compressor is attached to the body in such a way, that it can easily be removed. This is achieved by three rubber sockets, which provide the required stability and in addition reduce the vibrations that usually occur. The rubber sockets click in the bottom of the refrigerator and the feet of the compressor, see Figure 6.21. This solution facilitates disassembly as fixed joints are avoided and the compressor can easily be reached. Moreover, this design makes the automated disassembly feasible. First, the joint technique used is disassembly-friendly and the compressor can easily be separated from the refrigerator. Second, the fixed location of the compressor facilitates its identification by a vision system that can be introduced to monitor the automated disassembly.

| | |
|---|---|
| * | Replace the currently used CFC's with a compatible refrigerant |
| * | Reduce the number of non-compatible and non-separable materials |
| * | Find an alternative for the non-recyclable Formica table-top |
| * | Find an alternative for the currently used PUR-insulation material |
| * | Avoid fasteners and use disassembly-friendly joining methods |
| * | Attach the door so that it can be easily removed |
| * | Make the disassembly of the compressor easy and suitable for automatic disassembly |
| * | Facilitate the disassembly of the cooling system |
| * | Replace the currently used "sandwich" construction |

Table 1: Guidelines for the design of refrigerators.

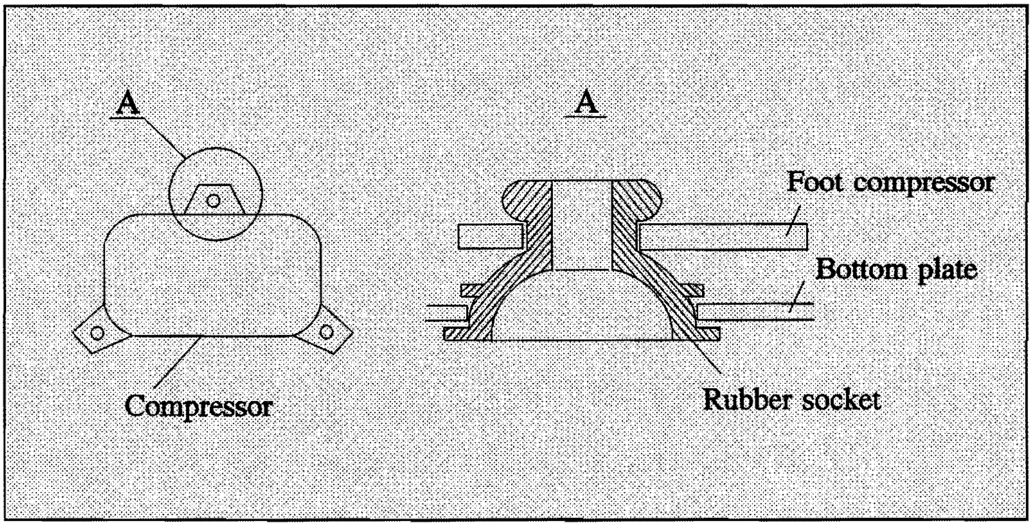



Figure 6.21: A general sketch of a compresor and a rubber socket.

In addition, the other guidelines also were considered and the completed design concept was developed. In this context, "sandwich" construction used in modern refrigerators is replaced by a modular design. The insulation and the inner layer are clamped between two panels and fixed with an upper frame. This makes the modular assembly of the refrigerator possible. The number of sub-assemblies are assembled together with the usage of fixed joints, so that the refrigerator can easily be disassembled. However, refrigerators are consumer products and they should preferably be considered for recycling than for disassembly. Therefore, in the beginning of the design process it should be made clear which changes will generate the optimal solution concerning the reduction of the total costs. In the new design the recycling aspect has also been involved. The number of plastics are reduced as the inner part of the case and the interior parts are made from the same plastics (ABS), which will facilitate their separation and recovery. However, in this way the refrigerator becomes more expensive. Therefore, total life-cycle cost accounting should be carried out to make clear if such changes are justified from an economic viewpoint. Furthermore, the freon is replaced by isobutane as a coolant and by pentane to form the insulation layer (expanded polystyrene). In this way, the usage of a degassing installation for the processing of PUR can be avoided, which will result in lower recovery costs. However, it should be emphasized that the described changes in refrigerator's design have not been validated by producers yet. This is because the new refrigerator's concept requires some changes in the production facilities and market strategy of a company. In this context, it is unrealistic to think that companies will abandon their currently optimized production facilities. In addition, it is still not clear if the customers will accept the suggested design from an economic and aesthetic viewpoint. For this purpose further research should be carried out to give the answer to these important questions. However, at the current moment the designers can make changes which contribute to the decreasing of the total life cycle costs of a product without causing drastic changes in the production facilities. In this context, the solution concerning the attachment of the compressor can be implemented in practice as it has an obvious contribution to the design of disassembly and recovery-friendly products.

### 6.5.2 General considerations for the design of recovery friendly household and electronic goods

The implementation of the disassembly line for various discarded goods, described in Section 6.4, has also contributed to the development of some design guidelines. This section gives these considerations which are common for the regarded household and electronic goods, see Table 2. For instance, the positioning and connection of the circuit boards is an apparent problem which can be observed by almost every type of the

Table 2: General considerations for the design of recovery friendly household and electronic appliances.

| | large household appliances | | refrig. | small househ. appl. | consumer electronics | | |
|---|---|---|---|---|---|---|---|
| | others | pur cont. | | | tv set monit. | comp. | others |
| Positioning and connecting of capacitors | X | X | | X | | | |
| Positioning and connecting of motor/compressor | X | X | X | | | | |
| Avoiding a sandwich construction with PUR-foam or glass wool | | X | | | | | |
| Positioning and connecting of gas-regulator | | X | | | | | |
| Connecting of housing with disassembly-friendly joints | | | | X | X | X | X |
| Positioning and connecting of circuit boards | | | | X | X | X | X |
| Reduction of joints diversity | X | X | X | X | X | X | X |
| Connecting the tube | | | | | X | | |
| Connecting of deflection unit in a disassembly friendly way | | | | | X | | |
| Positioning and connecting of frame-parts | X | X | | | X | X | X |
| Connecting of transformers to circuit board | | | | | X | X | X |
| Avoiding the application of various plastics | X | X | X | X | X | X | X |
| Avoiding the application of non-recyclable materials | X | X | X | X | X | X | X |
| Avoiding poisonous materials | X | X | X | X | X | X | X |

Symbols: X - issue to be considered by designers during the early design phase.

described discarded goods. In a new design, the circuit boards have to be positioned so that easy identification and disassembly is possible. This will lead to the introduction of more advanced processes and equipment for the recovery of this sub-assembly and for the processing of the available poisonous components (capacitors). Besides, attention should be given on the usage of recyclable and environmentally friendly materials. In general, the same conclusions can be drawn as described in the previous section. In this context, the joints have to be disassembly friendly and easy to attain. In addition, it is recommendable to design products which allow to be disassembled in a vertical direction.

The suggested design considerations, which are based on the experiences obtained during the recovery of various goods, have to be used by designers in the beginning of the design process. It is supposed that if they are taken into account, the designers will be better informed about the possible problems, so that they can be prevented on time. For this purpose, a number of pilot project concerning the design of sustainable products have to be carried out [GE, 1994]. In this way, the suggested guidelines can be verified and their validation can be specified.

## 6.6 Conclusions

The design and implementation of the disassembly systems, described in this chapter, show that the suggested systematic approach is a workable method that can be used when we look at disassembly and recovery issues. It gives the most important steps that should be carried out when designing disassembly systems. While these steps are valid for all types of discarded goods, there are some specific aspects that have a significant impact on the development process. In this context, the legislation rules should always be considered as they impose requirements that are compulsory. In addition, market developments, logistics, available customers for secondary parts and materials, and the policy of a company, are important issues that have to be taken into account in the early development phase. Based on the specific requirements generated by the above-mentioned aspects, the disassembly strategy has to be determined. This can be achieved by the application of the method for the determination of the disassembly strategy, which generates the optimal disassembly sequence and depth (level). In practice, it is found that the determination of the disassembly depth is the most important issue, as changes in the disassembly sequences are limited by technical and economic considerations. Moreover, the number of possible disassembly plans should be reduced because if their theoretical number is considered, the disassembly task will become extremely difficult and impossible to solve within a realistic time frame. In addition, the optimal disassembly plan is defined by the company's goal and legislation rules, so that a desired output flow can be generated. This implies that there is no common disassembly strategy and it depends on a number of specific aspects. Because the number of disassembly steps, which are included in a disassembly strategy, may be changed frequently, the corresponding disassembly system should be flexible enough to allow for any particular order in the recovery of discarded goods. Such a design of disassembly systems can be achieved by the application of the suggested systematic approach, as was described in this chapter. *However, the method described does not guarantee that optimal disassembly systems can be developed. In this context, the creativity and experience of the individual will always be necessary to achieve the established goals.*

In addition, it was shown that during the disassembly of discarded goods the most important problems concerning their recovery can be identified. The information obtained is used as an input to create new design rules, so that the current recovery problems can be avoided. This is the case in the new refrigerator design where the disadvantages concerning the attachment of the compressor are avoided in the new product, so that the refrigerator can be recovered with less costs. This fact makes the role of the recycling companies significant and confirms the need of their existence for the following reasons:

- Recovering the valuable components and materials from discarded goods.
- Reducing the impact of the huge flow of discarded goods.
- Providing information to establish design guidelines for the development of sustainable products.

In this context, designs teams and manufacturers have to involve the recovery option in their strategy concerning the design and production of recovery friendly products. Producers should use the experience of the recycling companies that are obtained during the disassembly of the current generation of discarded goods. This is the way to exchange reliable information about the design of recovery friendly products between the manufacturers and recycling companies, which is a significant issue. In addition, more efforts are required to establish a full life cycle analysis as was suggested in the general disassembly approach. In this way, positive and encouraging results can be expected as the total costs of the companies can be reduced and the environmental impact of discarded goods can be limited.

# Chapter 7

# General conclusions and recommendations for further research

## 7.1 Conclusions

The industrialized countries are aware of the potential for destruction on our planet if no measures are taken towards environmentally conscious design and manufacturing, and the processing of discarded goods. Some individuals may regard the recovery of discarded goods as a problem for rich countries. But the increasing flow of discarded goods, which also contain poisonous materials, should be regarded as a present and clear danger for the environment and consequently for the people's health. Therefore this problem can not be postponed and should be solved in a due course. With regard to the above, the aim of this dissertation is to support the current activities in the field of the recovery of discarded goods. Such activities are needed to close the product life cycle chain, which is an indispensable condition for the establishment of sustainable production. Besides that the recovery of discarded goods can be regarded as a business opportunity, because they can be processed in such a way that a certain profit can be generated. However, this is not possible without knowledge and experience of how to tackle this issue. In this context, this dissertation is mainly intended for companies that want to benefit from the opportunity, while fulfilling the legislation rules and contributing to the protection of the environment. In addition, producers of durable and consumer goods can use the results of this research to estimate what their total production costs will be when the recovery of goods is involved. In this way, they will be able to consider what changes can be done in the product design, so that the total costs can be reduced. Furthermore, the results of this research can be used by scientific institutions that investigate the establishment of a sustainable production on micro-economic level, in which the recovery of goods should also be involved.

It should be emphasized that this research suggests a way to solve the problem of the increasing flow of discarded goods now and in the coming decade. Moreover, this represents a business opportunity and there is no doubt that it should be realized while simultaneously investigating other issues related to the establishment of sustainable production. Regarding the experience gained by the execution of this research, the following conclusions can be drawn:

Conclusion 1: *Production chains should be closed with the recovery of discarded goods. This can be achieved by the introduction of disassembly systems, which requires further development of knowledge and experience in this new area.*

While every action towards the establishment of a sustainable production is valuable, it has been suggested that the design of disassembly systems is a significant issue in accomplishing this goal. The reasons for this conclusion are the following:

- Disassembly systems are a powerful weapon to attack the increasing flow of discarded goods now and in the future.
- Disassembly systems make it possible to close the production chain, which is one of the characteristics for a sustainable development.
- By means of disassembly the poisonous fractions with a high environmental impact can be removed and processed.
- By means of disassembly systems, valuable parts and materials can be recovered and reused, which is also a significant issue as the usage of raw materials can be reduced.
- The experience gained from the current disassembly facilities will help to establish the basis for the design of recovery and environmentally friendly products.

Concerning the above discussion, it was concluded in Chapter 1 that the design and implementation of disassembly systems is a significant issue that should be looked into as soon as possible. For this purpose a systematic design approach is required to facilitate the current developments in this field; this was formulated as the main issue of this thesis.

Conclusion 2: *There is no systematic disassembly approach concerning the design of disassembly systems.*

This conclusion is based on a comprehensive literature review, represented in Chapter 2. While various aspects of designing of "green" products and processing of discarded goods are discussed in the literature, there is no complete strategy that involves all important recovery aspects and gives a plan to solve the problems now and in the future. The absence of such a strategy makes the recovery issue complicated and discourages companies from considering this new important aspect. In this context, governments are introducing rules to push companies to consider the environmental and recovery issues. For instance, there are some regulations that prohibit storing poisonous waste in the landfill. In addition, the disposal costs are increasing tremendously and it is expected that the prices of raw materials will increase too. Furthermore, some bills have already been introduced that demand the manufacturers take responsibility for their discarded goods. These facts imply that companies which are considering the complete product life cycle will have an advantage in the international market, because they can reduce their total costs by avoiding disposal taxes and reusing some parts and materials. In addition, it is expected that companies with a "green" image will get a higher market share in comparison to their competitors.

Conclusion 3: *To be able to design an advanced disassembly system, one needs knowledge and experience concerning the simultaneous design of the product, process and the corresponding disassembly system.*

Although the design of disassembly systems is a new issue, it should be related to well known problems. In this context, the design theory, the theory of technical systems and the assembly knowledge and practice are significant for the development of the suggested systematic approach. The design theory provides a number of procedures that have been applied in design practice. These procedures focus the structuring of the design process to make the entire process easy to understand and execute. In addition, suitable design methods are suggested to solve problems within every design step. However, there is a danger of applying the existing design models and methods without considering the recovery issue. For this purpose, the designer's creativity is required in order to extend the available methods and to make them suitable to design recovery friendly products. In addition, the knowledge and experience from assembly should also be used to develop the systematic approach as assembly and disassembly generally are similar processes; this was discussed in Chapter 3.

Conclusion 4: *To develop a profitable disassembly process and system for specific applications, one has to be able to determine the optimal disassembly strategy for specific discarded goods.*

One of the significant issues concerning the recovery of discarded goods is the determination of the disassembly strategy. It gives the most feasible disassembly process one can apply to generate the maximum profit from the discarded goods. The disassembly strategy is based on economic and technical issues, while the specific legislation rules concerning safety and environmental protection are fulfilled. A method for the generation of the disassembly strategy was created in Chapter 4. It involves the following steps:

1) Generation of feasible disassembly plans; this task is accomplished by

application of the AND/OR graph method.

2) Determination of the profits per disassembly level; this task is realized by application of the mathematical tool developed in this dissertation.
3) Determination of the optimal disassembly process and depth; this is accomplished by application of the method of dynamic programming.

The proposed method for the determination of the disassembly strategy, which is based on these three issues, is universal and can be applied to all types of discarded goods. In this context, when a new generation of disassembly friendly products is offered for processing, the optimal disassembly plan for their recovery will be different from the old generation. However, this will be determined by the application of the suggested method in the way described in this dissertation. Based on the obtained results, the number of steps of any disassembly process can be defined and the corresponding system can be developed.

Conclusion 5: *By using the existing knowledge concerning the design of assembly systems and the method for the determination of the disassembly strategy, represented in Chapter 4, the design of a disassembly system can be achieved in a systematic way; this enables one to generate an optimal disassembly system concept for specific goods.*

The suggested systematic approach presents a procedure that gives the process of development of disassembly systems in a systematic order. The aim is to support companies that want to set up disassembly plants. By using this approach they will be able to consider all important aspects and to go through all necessary steps, so that the optimal design of a disassembly system can be achieved, which implies the generation of the desired profit from recovery.

Conclusion 6: *An optimal disassembly system can be designed for specific discarded goods, while considering specific requirements and constraints.*

The systematic approach was applied in practice to design various disassembly systems. In this context, three disassembly systems were developed for the recovery of household appliances and diverse consumer electronic goods, as was described in Chapter 6. These types of products cover various problems associated with the recovery of discarded goods. This proves that the applicability of the suggested approach is universal and can be used when considering disassembly issues, including the recovery of the next generation of products. During the application of the systematic approach, it was observed that the disassembly systems developed for discarded electronic goods differ, as is described in sections 6.3 and 6.4. In general, they may be similar because the legislation and recovery requirements are common to all discarded electronic goods. However, another very important aspect that influences the design of an optimal disassembly system is the business strategy and philosophy of the firm. Such a strategy depends on the market for the recovered materials (components) and determines the characteristics of the output flow. Furthermore the output flow determines the disassembly strategy and consequently the configuration of the corresponding disassembly system. In addition, taking into account other aspects such as labour rate, machine and technology costs, one can imagine that there is not just one optimal disassembly system for specific discarded goods. Moreover, the optimal disassembly strategy should be upgraded and adapted continuously to specific demands from the market or legislation. This requires the introduction of disassembly systems able to respond to all changes in the flow of discarded goods. In brief, the systematic approach gives the procedure needed to design an optimal disassembly system concerning defined constraints and in a specific environment. Any change of the constraints or in the environment will influence the final disassembly configuration. However, the systematic approach needed to achieve such an optimal disassembly system design will remain the same.

Conclusion 7: *The systematic approach for the design of disassembly systems can be regarded as part of a systematic plan for the establishment of a recovery strategy.*

For this purpose, all the elements of the general life cycle model, as suggested in Figure 5.2 (Chapter 5), should be worked out in detail. In this way, in due time, the recovery activities can be supported, which is a significant issue nowadays. It implies that economic growth should not be at the expense of nature. The most important issue is that economic growth and environmental protection should complement each other and work in tandem. It should be realized that this will take time and will require sacrifices from society as a whole. However, until everyone is aware of this need, legislation remains the main factor that can support and push the establishment of recovery facilities.

## 7.2 Recommendations for further research

During the development and implementation of disassembly systems, various industrial engineering aspects have been considered and their influence on the recovery of discarded goods has been clarified. However, not every issue has been carried out in detail. In this context, the recommendations for further research are related to some aspects of recovery that have to be investigated further. They have been included in the general disassembly plan for the recovery of discarded goods (see Figure 5.2).

Recommendation 1: Research should be done to find out what product design changes can be proposed for the companies in the short term, so that recovery and environmentally friendly products can be produced with the available technologies and equipment. In parallel, long-term changes should be considered as well, so that companies will be able to produce sustainable products at optimal costs.

Recommendation 2: Research can be formulated that will consider the possibilities and consequences of leasing. This is an important issue that may have a great influence on the recovery of discarded goods. A hypothesis was made that leasing would encourage companies to think about the entire product life cycle to a greater extent. This is because the manufacturers remain the owner of the products after they are discarded by the customers. It is important to know what the consequences will be for the economy, policy of the firm and customer's behaviour if leasing is introduced. In addition, an answer should be given as to how total cost accounting can be applied.

Recommendation 3: Research can be carried out concerning the creation of a secondary market for the recovered goods, components and materials. In addition, it is important to define what the optimal logistical framework should be and how to distribute the recovered goods in the most efficient way according to their quality, quantity and customer's orders. Furthermore, the recovery of goods will also affect the company's financial system. In this context, an optimal solution for a proper financial policy should be found, so that a maximum profit from recovery can be obtained.

Recommendation 4: It is necessary to introduce an international standard that provides the required information during the recovery of discarded goods. This involves the rapid identification of the various parts in an assembly, determination of their quality and determination of the form deviations during the exploitation. There are several possibilities to prepare information for disassembly and recovery of discarded goods and to present them to the processing companies. A simple bar-code or electronic chip may be considered as information carriers. They can provide data concerning changes in the product before it is offered for recovery. In addition, the disassembly information may be visualized to the companies by product drawings and the corresponding data on a World Wide Web page via the international network. Based on this information the process planners and/or operators can decide which disassembly operations should be carried out and what way is the most efficient. How this goal can be accomplished is a subject for further investigation.

Recommendation 5: The suggested method for the determination of the disassembly strategy should be computerized resulting in a software tool for process planning. This will facilitate the development of the optimal disassembly process and the recovery of discarded goods considerably.

Recommendation 6: Based on the experience obtained from the disassembly of discarded goods, design guidelines should be developed and involved in a complete expert system for the concurrent design of recovery friendly products, processes and systems. In this way, all important aspects will be considered during the early design stage, which will result in the development of recovery and environmentally friendly products.

Recommendation 7: It is supposed that in the future disassembly companies can only survive if automated devices are introduced in combination with people. Therefore, in parallel with the design of new products, research has to be carried out concerning the development of advanced disassembly processes and systems. This includes, among other things, the development of a software and hardware for quick image processing of components (material fractions) and their automated disassembly and recovery.

Recommendation 8: It is important to define who will be responsible and who will pay the cost for the processing of discarded goods and for the establishment of sustainable production. Putting all responsibility on the shoulder of the producer may not be a good solution. It should be clear that sustainable production requires sacrifices from all of society. Optimal results in terms of the preservation of value, resources and nature can only be achieved on the basis of shared responsibility. This will lead to the generation of maximum economic and environmental results at a minimum cost.

Recommendation 9: Further research should be carried out concerning the optimization of energy use during the complete production chain including recovery. It has to be specified how much energy is needed for the recovery of discarded goods and what is the acceptable limit, so that recovery can remain a profitable and environmentally friendly activity. In general, it should be made clear what the effects are from the establishment of sustainable production concerning the energy consumption.

The suggested research issues are important for the establishment of a sustainable development. Their execution will make a considerable contribution to achieving satisfactory results in this important field.

## Appendix 3.1

### Design for assembly worksheet

(initial design)

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Name of assemly " Roller " |
|---|---|---|---|---|---|---|---|---|---|
| Part i.d. no | Number of times the operation is executed | Two-digit manual handling code | Manual handling time per part | Two-digit manual insertion code | Manual insertion time per part | Operation time (2) x [(4)+(6)] sec. | Operation costs 0.4 x (7) cents | Estimation of minimum parts | |
| 7 | 1 | 90 | 2.2 | 06 | 5.5 | 7.7 | 3.1 | 1 | Pipe |
| 6 | 2 | 00 | 1.1 | 03 | 3.5 | 9.2 | 3.7 | 1 | Bearing unit |
| 5 | 1 | 00 | 1.1 | 00 | 1.5 | 2.6 | 1.0 | 1 | Axis |
| 4 | 2 | 05 | 1.8 | 01 | 2.5 | 8.6 | 3.4 | 0 | Rubber seal |
| 3 | 2 | 08 | 2.5 | 30 | 2.0 | 9.0 | 3.6 | 0 | Lock washer |
| 2 | 2 | 00 | 1.1 | 31 | 5.0 | 12.2 | 4.9 | 0 | Cup |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | 49.3 | 19.7 | 3 | design efficiency $\frac{3xNM}{TM}$ 18 % |
| | | | | | | TM | CM | NM | |

This appendix clarifies the analysis carried out using a design for assembly form or worksheet. A row of the form is completed for each component in some order of assembly. The completed worksheet provides a quantitative way of measuring the performance of a design concerning its ease of assembly. In this way, the presented worksheet can be used as a basis for comparing alternative designs and selecting the best one.

Column 1 contains the identification numbers (i.d.) of all parts of an assembly. The base has the highest i.d. number and can be found in the first place of the column. Every next part has a lower i.d. number. In other words, the numbers of the column should always be in descending order. Column 2 gives information about how many times an identical operation is carried out with a part. The inserted number is "1" if the operation is carried out only once at a given stage of assembly, "2" if two identical tasks are performed consecutively and so on. Column 3 gives a two-digit number that is chosen from a chart and represents the level of difficulty for the handling operations [Boothroyd, 1984]. Based on the selected number, the handling time per part is determined. In a similar way, column 5 and 6 represent the two-digit insertion number and the corresponding time. Based on the above, the operation time is calculated and inserted in column 7. For this purpose, the handling and insertion time are added and then multiplied by the value of column 2. In column 8, the operation cost is found by multiplying the value of column 7 by 0.4. Column 9 gives the theoretical minimum number of parts in an assembly. This is defined by applying Boothroyd's fundamental questions to every part (see to Chapter 3). A part can be rejected if all the answers are negative: in this case a "0" is inserted in the column 9. Otherwise "1" is entered which means that the component is a compulsory part of the assembly.

With the aforementioned information, the *design efficiency* can be found. It is defined as the ideal time (3.NM) divided by the calculated assembly time (TM) given in column 7. In other words, the design efficiency can be found in the following equation:

$$DE = \frac{3.NM}{TM} \qquad (1)$$

where:
- NM - the total theoretical minimum number of parts
- TM - total operational time
- 3 - expresses an assumption about the ideal time for handling and insertion of a part.

With this step the worksheet is completed and the designer can select the best design according to the requirements.

# Appendix 3.2

## Design for assembly worksheet

(new design)

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | Name of assembly " Redesigned Roller" |
|---|---|---|---|---|---|---|---|---|---|
| Part i.d. no | Number of times the operation is executed | Two-digit manual handling code | Manual handling time per part | Two-digit manual insertion code | Manual insertion time per part | Operation time sec. (2) x [(4) + (6)] | Operation costs cen. 0.4 x (7) | Estimation of minimum parts | |
| 6 | 1 | 00 | 1.1 | 00 | 1.5 | 2.6 | 1.0 | 1 | Pipe |
| 5 | 2 | 00 | 1.1 | 00 | 1.5 | 5.2 | 2.1 | 1 | Cup |
| 4 | 2 | 03 | 1.7 | 00 | 1.5 | 6.4 | 2.6 | 1 | Rubber seal |
| 3 | 2 | 83 | 5.6 | 01 | 2.5 | 16.2 | 6.5 | 1 | Hub with bearing |
| 2 | 2 | 00 | 1.1 | 01 | 2.5 | 7.2 | 2.9 | 1 | Axis |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | 37.6 | 15.1 | 5 | design efficiency $\frac{3xNM}{TM}$ 40 % |
| | | | | | | TM | CM | NM | |

This appendix represents the assembly worksheet of the redesigned roller. The form is created in the same way as was described in Appendix 3.1. It can be seen that the calculated design efficiency of the redesigned roller is substantially higher than the initial design.

# Appendix 4.1

## Possible disassembly alternatives for a bearing unit

This appendix describes all possible disassembly operations according to the AND/OR graph given in Figure 4.8, Chapter 4. There are two possible disassembly plans (A and B), which consist of a number of disassembly operations. In accordance with the graph, the disassembly process can be carried out in the following ways:

o *Disassembly plan A*

First, the axis (pos.1) is disassembled and the remaining parts (pos.2, 3, 4 and 5) are regarded as a sub-assembly that has to be further disassembled. This can be achieved in three different ways:

Alternative 1:

The hub (pos.2) with the bearing (pos.3) are separated from the cup (pos.5) with the rubber seal (pos.4). The two sub-assemblies obtained are represented at level 2, see (pos.2, 3) and (pos.4, 5) in Figure 4.8. Then the sub-assemblies are disassembled by the removal of the remaining two components.

Alternative 2:

First, the hub (pos.2) is removed from the remaining parts (pos.3, 4, 5) by means of a special press. This is followed by the disassembly of the bearing unit (pos.3) from the remaining parts (pos.4, 5). Finally, the seal (pos.4) is separated from the cup (pos.5).

Alternative 3:

First, the bearing (pos.3) is removed by means of a special press. After this destructive operation the remaining components (pos.2, 4, 5) are no longer fixed, but they are clamped together and have to be separated further. As a result, the following step is the separation of the hub (pos.2) from the remaining parts (pos.4, 5). Obviously, the last step is the separation of the rubber seal (pos.4) from the cup (pos.5).

o *Disassembly plan B*

First, the hub (pos.2) is removed from the remaining parts (pos.1, 3, 4, 5) by means of a special press. Then we have the disassembly of the axis (pos.1); the remaining sub-assembly consists of three parts (pos.3, 4, 5). The next logical step is to disassemble the bearing (pos.3) and finally to separate the rubber seal (pos.4) from the cup (pos.5).

# Appendix 5.1

## User mode and effects analysis

During usage most of the products are repaired in order to extend their useful life. In addition, products are used in different environments so that the characteristics of their components and materials are changed. While determining the disassembly strategy, it is significant to know what is the functionality of parts and what is the quality of materials. In addition, deviations that occur during usage due to the replacement of parts or other effects should be known. This requires the introduction of a suitable method that describes all the deviations of goods and what consequences should be taken into account when one is developing the optimal disassembly process. For instance, if a product has been used in a humid environment, the disassembly planner should consider corrosion of parts, which may result in specific problems during disassembly. This will require particular solutions to help prevent the machine's technical failure as a result of the described deviation. Another example is the usage of cars by different type of drivers, which may result in discarded cars with less or more exhausted parts. It is obvious that this changes the disassembly strategy as regards which parts should be recovered.

A method that can be used to provide the required information during disassembly is called User Mode and Effects Analysis. As we mentioned before, it can be compared with the Failure Mode and Effects Analysis (Process) method, which identifies failure in the process due to improper product design [Ford, 1988]. In addition, this method assesses the potential effects of the failure and establishes a priority system for corrective actions. When potential failure modes are identified, the corresponding actions can be initiated to eliminate them or continuously reduce their potential occurrence. In the same way by using the UMEA method, failures that may occur during recovery can be eliminated or reduced. In other words, the analysis of the usage mode will provide the information about the expected effects during disassembly and recovery. For this purpose the chart given in Figure 1 can be used. It consists of the following columns:

1) Number of action.
2) Name of a part or process step (tells us which item is considered).
3) Function (describes the function of the corresponding part).
4) Failure modes (gives comprehensive information about the expected failures).
5) Cause (describes the reason of the failure).
6) Effects on process level (describes what problems can be expected during disassembly and recovery).
7) P: probability of occurrence.

8) S: severity of the failure.
9) Recommended actions (gives procedures to prevent the identified failures).
10) Responsible (tells us who is responsible for the actions that should be taken).

| User mode and Effects Analysis | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Subject: | | | | | | | | | |
| 1. N | 2. Name of part or process step | 3. Function | 4. Failure mode | 5. Cause | 6. Effect on process level | 7. P | 8. S | 9. Recommended action | 10. Responsible |
| | | | | | | | | | |

Figure 1: An UMEA's chart.

With the help of a ranking method, using the probability of occurrence and the severity of the failures, the real weak points during disassembly and recovery can be established and the corresponding preventive actions can be taken. It is suggested that most of the problems due to a lack of information can be solved during the development of the disassembly process. This will result in a reliable disassembly process, which is a significant issue for the development of the most feasible disassembly system.

# Appendix 5.2

## Shredding and separation of materials

After accomplishing the required disassembly operations according to the disassembly strategy, the remaining material fractions of the discarded goods are sent to a shredder. As was already explained, shredding aims to reduce the total recovery costs. After shredding, a mixed flow of various materials is produced. They should be separated to obtain pure material fractions according to the established goals. This appendix gives a brief description of a general shredding installation and the most frequently used separation techniques. They should be considered when designing disassembly systems.

### 1) Shredding installation

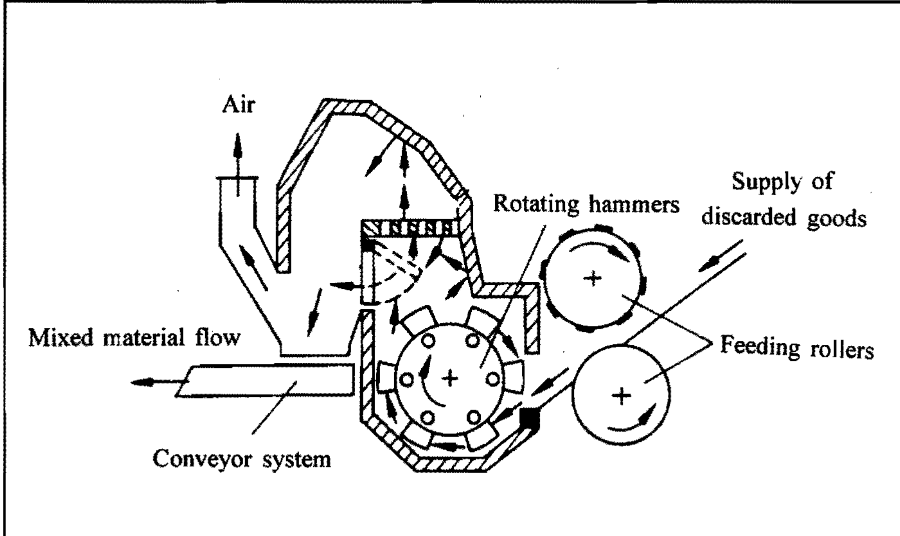



Figure 1. A general sketch of a shredding installation.

Shredders are technical devices that consist of a set of rotating hammers, see Figure 1. They are built in a large variety of sizes and with hourly capacities of 10 to 120 tons. Every single case requires accurate examination to determine the correct choice of shredder. This involves selecting the profiles, the thickness and the setting of the cutters on the shafts. In shredders, the remaining fractions of the discarded goods are supplied to the shredder's hopper by means of conveyor systems. Then the discarded goods are compressed and fed into a drum, after which they are demolished by a set of rotating hammers. This process continues until the scrap is small enough to drop out of an output grid. Then the separation of the materials fractions follows.

**2) Magnetic separation**

One of the fractions with the highest percentage in the mixed flow that should be recovered is the ferrous fraction. For this purpose magnetic separation techniques have to be applied. The principle of magnetic separation is given in Figure 2.

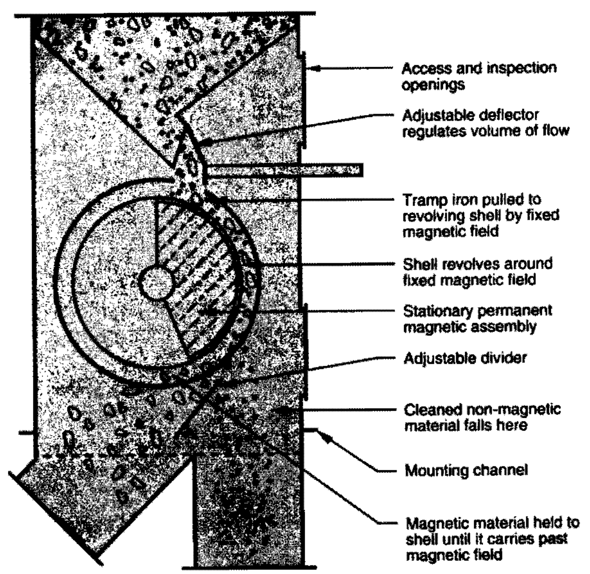



Figure 2: Principle of magnetic separation.

There are various devices for magnetic separation. In this context, the following techniques are usually used in practice [Goudsmit, 1993]:

a) Permanent magnetic drum separation:
   - Cris-Cross Circuit Drum.
   - Rare Earth Drum.
   - Agitator-Type Drum.
   - Drum in Housing with Feed Protection.

b) Electrical block magnet.

c) Electrical overbelt magnet.

d) Permanent overbelt magnet.

e) Permanent magnetic headroller.

f) High-gradient magnetic separation.

The kind of magnetic system that should be chosen depends on the materials in the flow and the percentage of ferrous fraction in it. The separation process can be briefly described as follows. As the material flow reaches the drum, the magnetic field attracts and holds ferrous fractions. When the drum rotates it moves the material stream through the stationary magnetic field. Because of the gravity force, the non-ferrous materials fall from the drum shell. The ferrous materials are held until they are carried out from the magnetic field. Then the obtained materials are transported to their end destination.

**3) Eddy current separation**

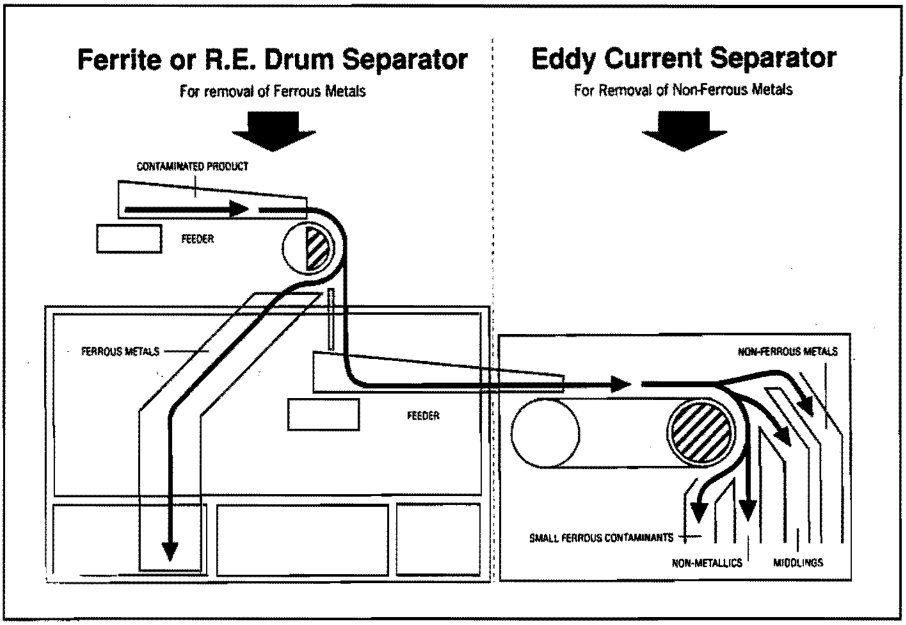



Figure 3: Principle of magnetic and Eddy current separation.

After the ferrous fractions are separated, the next step is to separate the non-ferrous metal by means of Eddy current separators, see Figure 3. They can physically separate non-ferrous metal such as copper, aluminum and zinc. The principle of Eddy current is that an electric charge is induced into a conductor by changes in a magnetic field. These currents induce a secondary magnetic field around the material fractions, which reacts with the magnetic field of the rotor. This causes combined drilling and repelling forces. The repelling force ejects the conducted non-ferrous metal fractions from the production stream.

Various factors influence the separation of materials. To develop a reliable process, one should execute laboratory tests to define the best type of separation technique and parameters concerning a given range of goods. The following variable factors have a significant influence on the separation process [Eriez Magnetic Ltd., 1992]:

- Particle shape.
- Particle size.
- Particle conductivity.
- Density.
- Moisture content.
- Stickiness.
- Size distribution.
- Fibrous content.
- Metallic content.

In addition, the performance can be affected and optimized by varying the following parameters:

- Belt speed.
- Rotor speed.
- Feed method.
- Design of the rotor.
- Spitters setting.

Eddy current is an important technique as it allows the separation of nobel material fractions. This results in the generation of high revenues, which is essential for accomplishing the established goals.

### 4) Ballistic separation

The separation of rubber, glass, and plastic fractions can be achieved by the application of ballistic techniques. For this purpose the fractions are moved on a conveyor system. At the end the fractions leave the conveyor with the same speed. Because some of them are lighter than the others, they follow different curves before falling down in containers.

### 5) Riddle

The riddle process aims to classify particles by their dimensions. A mixture is separated into two parts, one fraction of particles pass the opening of the riddle while the other part remains on the riddle area. By using more riddles in cascade a separation into more than two parts can be obtained. In practice, drum riddles, shake riddles and vibration riddles are used.

### 6) Wind sifter

By means of a wind sifter it is possible to separate solid particles because of different densities, forms and dimensions in an air flow; the particles are classified by their gravity. Light particles are transported to the upper side by the air flow, while heavy particles fall down. Wind sifters are available in different types, which can vary from a vertical to a horizontal tube and from a straight to a zigzag tube.

### 7) Gas cyclone

The gas cyclone separates solid particles from a gas because of a difference of densities and dimensions by means of centrifugal forces. They are mainly used to extract dust from the air. Another type of separation equipment utilizes wet separation techniques by using a liquid as a working medium. The techniques are based upon the principle that solid particles can be separated from a mixture of solid particles and liquid by means of different particle dimensions and/or density. The most important techniques are:

### 8) Float-sink technique

This technique is applied to separate solid particles by means of differences in density. The particles that have to be separated are immersed in a liquid with a density value between the density values of the both components to be separated. The heavier particles sink down to the bottom, while the lighter particles float at the surface.

### 9) Hydrocyclone

Hydrocyclone is used to separate solid particles from a liquid based upon differences of density and dimensions by means of centrifugal forces generated by the particles themselves in a whirl. It is used also to separate a contaminant from a liquid.

After the valuable fractions are extracted from the material flow by means of various separation techniques, not more than 2% - 3% scrap remains that is disposed. With this step the entire separation is accomplished. The obtained result should be reusable pure materials that are produced in an environmentally sound way.

# Appendix 6.1

## Alternative disassembly plans for the recovery of a refrigerator

This appendix describes the other possible disassembly plans for the disassembly and recovery of refrigerators. The plans are generated by the application of the AND/OR graph method and shown in Figure 1, 2 and 3.

*1) Disassembly alternative 2*

The second disassembly alternative includes first the extraction of the freon and oil, because these operations have to be carried before the others, as was already explained. The main difference of this alternative (see Figure 1) in comparison to the first one is that the glass is shredded. This results in higher separation costs and lower revenues as pure glass fractions can hardly be obtained after shredding. In addition, the cables are removed inside of the factory. Then they have to be transported outside in the corresponding containers bringing higher transport costs. In addition, the remaining part of the refrigerator is shredded as was described in Section 6.2. The disassembly graph includes the following operations:

1) Extraction of freon and oil.
2) Dismantling of the compressor.
3) Removal of loose plastics (boxes).
4) Shredding of the remaining fractions.

Based on the above plan, the maximum profit found is equal to 2.82 [money units].

*2) Disassembly alternative 3*

In alternative 3, the glass and cables are removed inside the factory. The other operations and depth are the same as in alternative 1. In other words, the following disassembly operations are included:

1) Extraction of freon and oil.
2) Dismantling of the compressor.
3) Removal of glass.
4) Removal of loose plastics (boxes).
5) Removal of cables.
6) Shredding of the remaining fractions.

This process generates a maximum profit of 2.85 [money units].

*3) Disassembly alternative 4*

In alternative 4, the oil and the freon are extracted. In addition, the compressor is dismantled and the remaining part of the refrigerator is shredded. In other words, in this case only the compulsory operations are carried out, followed by shredding. The separation of the mixed material flow results in the generation of a limited percentage of pure material fractions implying low revenues. The disassembly plan includes the minimum number of operations:

1) Extraction of freon and oil.
2) Dismantling of the compressor.
3) Shredding of the remaining fractions.

Based on the this process, the maximum profit equals 2.41 [money units].

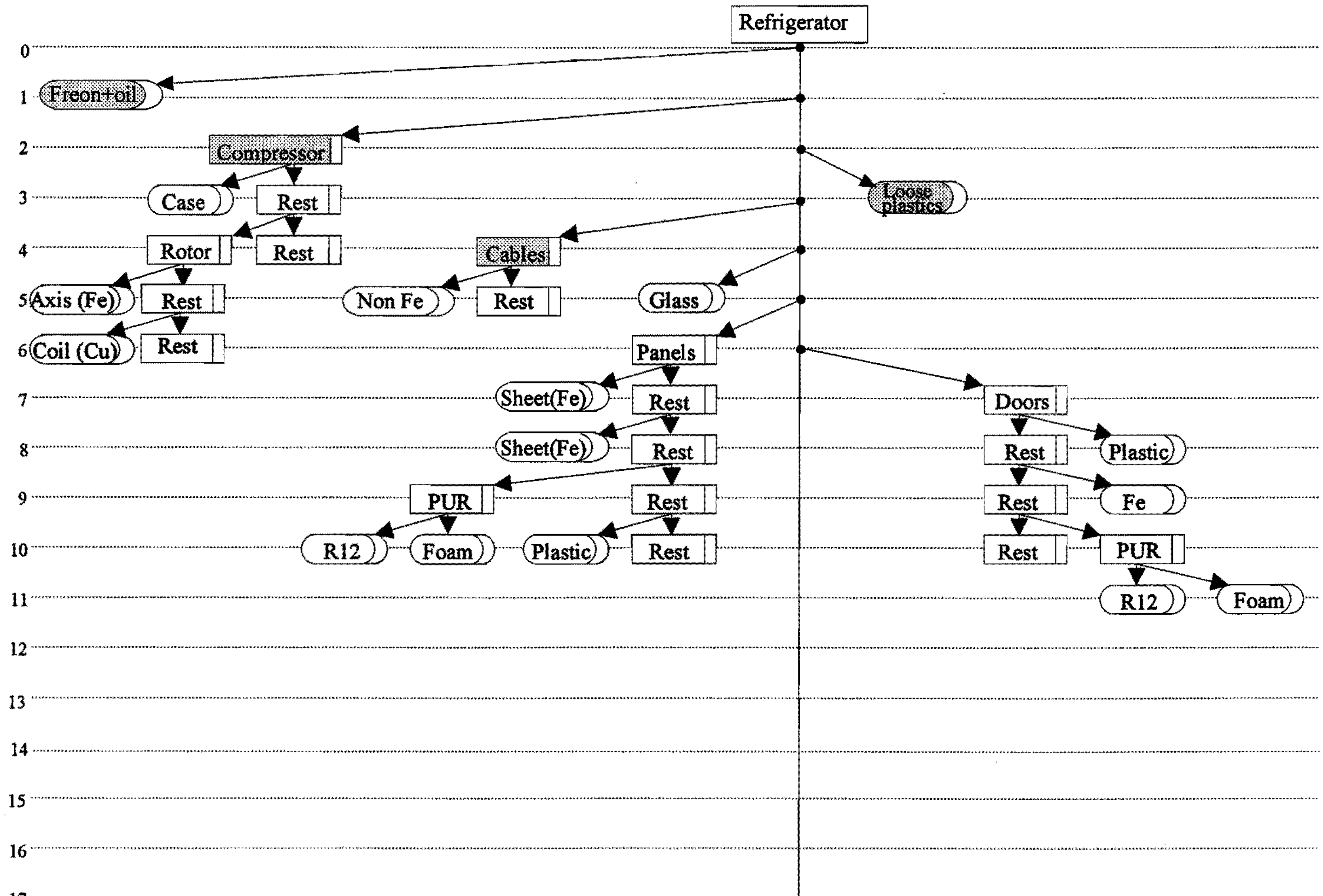



Figure 1: Disassembly alternative 2.

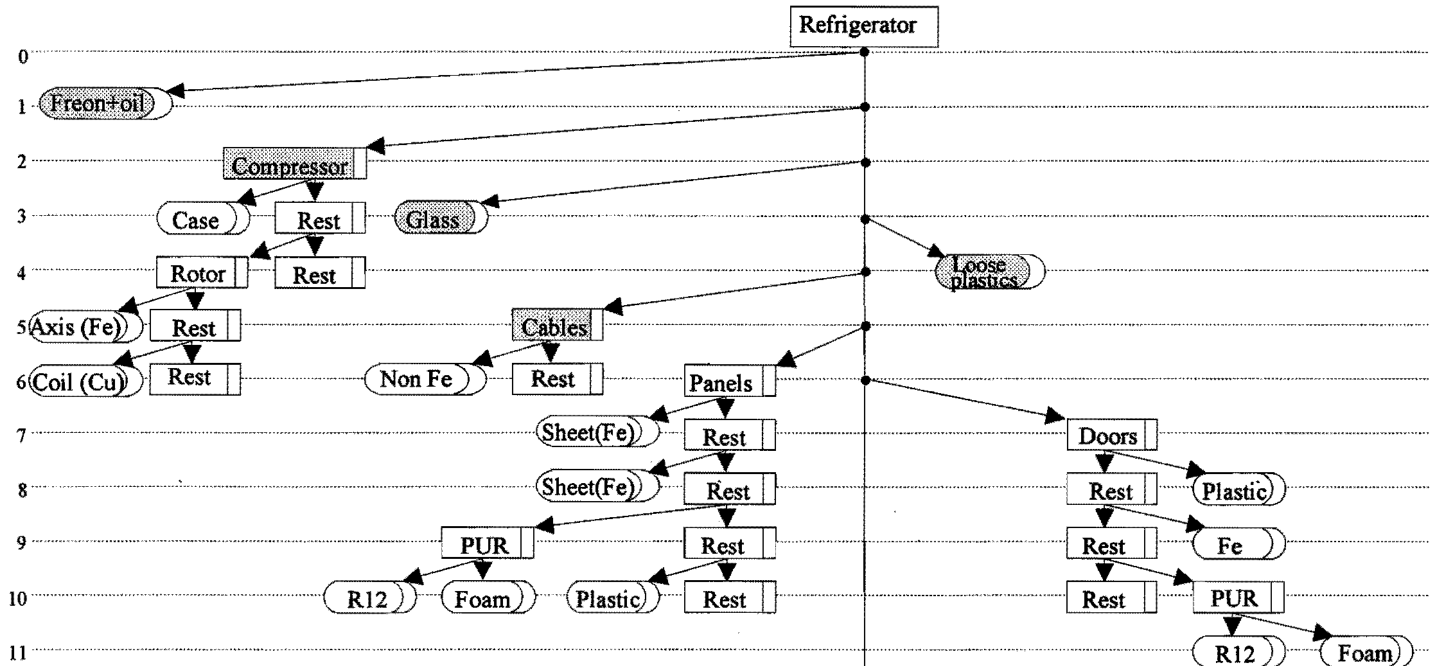



Figure 2: Disassembly alternative 3.

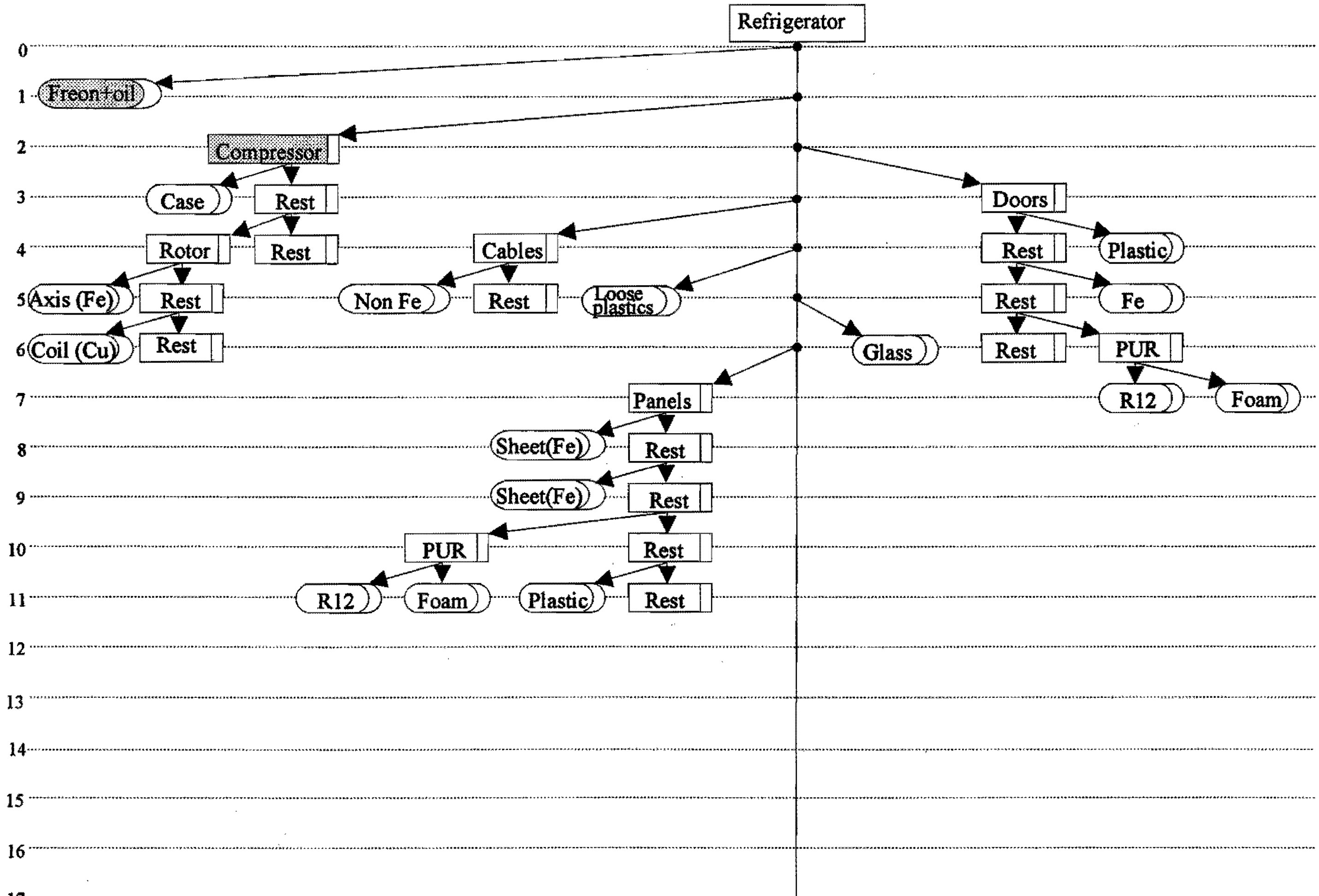



Figure 3: Disassembly alternative 4.

# Appendix 6.2

## Evaluation of the alternatives
### (household goods)

To accomplish the evaluation, the criteria selected are mutually compared. The best in every case receives 2 points, the worst 0 point and 1 point is given for equal importance. At the beginning of the evaluation we have to determine which criteria are significant for the development of the disassembly system. In this way, a selection can be made with reasonable accuracy. For instance, one of the most important criteria in this case is the generation of higher revenues and increasing the total productivity. This can be explained by the fact that a firm is always interested in attaining its primary object: the generation of a certain profit. Only in this way, the company can be competitive and survive in the recovery business. Therefore, these criteria will get a higher weight factor than the others. In addition, the reduction of the freon emissions is also an important issue and in general it will have a high priority too. However, with the initial dismantling process the company was able to process 98% of the freon available in the refrigerators. It is obvious that further improvement can hardly be achieved and decreasing the freon emissions was not considered as a criterion during the evaluation. Table 1 represents the result of the mutual comparison of the selected criteria. Based on the total score, a weight factor is assigned to every criterion. However, not every criterion receives the same weight factor. In other words, it is necessary to reconsider the obtained results if they do not fulfil the established perceptions and requirements. For instance, it can be seen from Table 1 that criteria 2 and 6 generate a different total score. However, they are equally important for the company. Therefore, they receive the same weight factor. In a similar way, all criteria selected are considered, so that a reliable weight factor can be assigned to them.

The next step is the evaluation of the system alternatives developed. For this purpose the alternatives and criteria are listed in a table where the total score can be obtained, see Table 2. Every system concept receives 1, 2, 3, 4 or 5 points, depending on the extent to which it fulfills the corresponding criteria. By multiplying the weight factor of the criteria and the points given to every alternative, the final total score is obtained. It is used to compare and select the system alternative with the highest score. It is recommended that one carry out this evaluation with various weight factors, as preference may be given to other criteria. The goal is to check the sensitivity of the selected method in case the priority is changed for any reason. In this case, alternative 4 gets the highest score and should be considered for implementation.

Table 1: Comparison of criteria.

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | T | W |
|---|---|---|---|---|---|---|---|---|---|
| 1. Improved logistics | | 0 | 1 | 1 | 1 | 1 | 1 | 5 | 5 |
| 2. Increase of the total productivity | 2 | | 2 | 2 | 2 | 1 | 2 | 11 | 10 |
| 3. Facilitating worker's operations | 1 | 0 | | 1 | 2 | 0 | 1 | 5 | 7 |
| 4. Achieving a flow production | 1 | 0 | 1 | | 0 | 0 | 0 | 2 | 2 |
| 5. Decreasing inventory | 1 | 0 | 0 | 2 | | 0 | 0 | 3 | 3 |
| 6. Increasing revenues | 1 | 1 | 2 | 2 | 2 | | 2 | 10 | 10 |
| 7. Increasing worker's satisfaction and motivation | 1 | 0 | 1 | 2 | 2 | 0 | | 6 | 8 |

T = total score  W = weight (highest score = 10)

Table 2: Evaluation of the developed alternatives.

| Criterion | | W | Alternative layout's number 1 | 2 | 3 | 4 | Short description |
|---|---|---|---|---|---|---|---|
| 1 | Improved logistics | 5 | 2 | 3 | 4 | 5 | Alternative 4 provides an optimal supply of refrigerators, their processing and transportation. |
| | | S | 10 | 15 | 20 | 25 | |
| 2 | Increase of the total productivity | 10 | 3 | 4 | 3 | 5 | The highest score is given to alternative 4, because it has the highest productivity expressed in a numerical value. |
| | | S | 30 | 40 | 30 | 50 | |
| 3 | Facilitating worker's operation | 7 | 3 | 4 | 5 | 4 | The introduction of a robotic system in alternative 3 facilitates the worker's operations the most. |
| | | S | 21 | 28 | 35 | 28 | |
| 4 | Achieving a flow production | 2 | 2 | 3 | 3 | 4 | Alternative 4 provides the optimal flow of goods and materials within the factory. |
| | | S | 4 | 6 | 6 | 8 | |
| 5 | Decreasing inventory | 3 | 2 | 3 | 4 | 4 | Alternative 3 and 4 have the lowest inventory level. |
| | | S | 6 | 9 | 12 | 12 | |
| 6 | Increasing revenues | 10 | 4 | 4 | 4 | 4 | The obtained revenues are the same for all alternatives. |
| | | S | 40 | 40 | 40 | 40 | |
| 7 | Increasing worker's satisfaction and motivation | 8 | 2 | 3 | 4 | 3 | The high level of responsibility in alt. 3, motivates the operators the most. |
| | | S | 16 | 24 | 32 | 24 | |
| Total score | | | 127 | 162 | 175 | **187** | |

# Appendix 6.3

## Evaluation of the alternatives
### (household and electronic goods)

To accomplish the evaluation, the established criteria have to be compared to each other. Score 2 means that the first criterion is most important, score 1 that they are all equally significant, and score 0 means that the first criterion is less important. Based on the total score, a weight factor is assigned to every criterion, which is used during the selection phase. The obtained results are compared with the required investment to implement a concept. In this way, the most suitable solution can be found that fulfils technical, economic and some social requirements. It has been suggested that the optimal system can be selected in this way [Metzger, 1977].

Table 1 gives the results of the comparison of the criteria that determine the weights. The obtained results from the above matrix are used to select the most feasible disassembly system. This is achieved by using the (technical and social) criteria and the corresponding weights. In Table 2, the alternative concepts 1 to 5 are compared. An alternative receives 5, 3 or 1 point, depending on the way it fulfils the criteria. In the last row, the final score for each concept is presented. These results are related to the investments needed to build these systems. This should lead to the optimal alternative for the disassembly system. However, at present it is difficult to determine the exact investments for the alternatives. Therefore, a rough estimation is given for the investment level. The costs for work stations and means of transport are nearly equal for all alternatives. The difference in costs between the alternatives is mainly related to the changes in the existing configuration. For concepts 1, 3 and 5 the existing configuration of the material separation installation has to be changed; this means higher costs. For alternative 2 and 4 the existing configuration can be maintained.

Table 1: Determination of the weights of the selected criteria.

| Criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | T | W |
|---|---|---|---|---|---|---|---|---|---|
| 1. Flexibility with regard to quantity of products and changes in the lay-out | | 1 | 1 | 2 | 2 | 2 | 2 | 10 | 9 |
| 2. Easy maintenance | 1 | | 0 | 2 | 2 | 2 | 2 | 9 | 8 |
| 3. Total productivity | 1 | 2 | | 2 | 2 | 2 | 2 | 11 | 10 |
| 4. Easy handling and piece flow production | 0 | 0 | 0 | | 2 | 1 | 1 | 4 | 5 |
| 5. Possibility for communication between operators | 0 | 0 | 0 | 0 | | 1 | 1 | 2 | 3 |
| 6. Change in work intensity | 0 | 0 | 0 | 1 | 1 | | 1 | 3 | 4 |
| 7. Safety and ergonomic conditions | 0 | 0 | 0 | 1 | 1 | 1 | | 3 | 4 |

T = total score W = weight (highest score = 10)

Table 2: Comparison of the alternatives.

| Criteria | | W | Number of alternatives 1 | 2 | 3 | 4 | 5 | Short description |
|---|---|---|---|---|---|---|---|---|
| 1 | Flexibility with regard to quantity of products and changes in lay-out | 9 | 5 | 5 | 3 | 1 | 3 | Alt. 4 is based on the initial system, therefore it is less flexible. |
| | | S | 45 | 45 | 27 | 9 | 27 | |
| 2 | Easy maintenance | 8 | 5 | 5 | 3 | 1 | 3 | Alt. 1 and 2 offer easier access to the equipment. |
| | | S | 40 | 40 | 24 | 8 | 24 | |
| 3 | Total productivity | 10 | 5 | 5 | 3 | 1 | 3 | Alt. 1 and 2 have the highest calculated productivity. |
| | | S | 50 | 50 | 30 | 10 | 30 | |
| 4 | Easy handling and piece flow production | 5 | 3 | 5 | 3 | 1 | 1 | Alt. 2 provides easier handling and transportation. |
| | | S | 15 | 25 | 15 | 5 | 5 | |
| 5 | Possibility for communication between operators | 3 | 5 | 3 | 1 | 3 | 3 | In alt. 1 the operators are close to each other. |
| | | S | 15 | 9 | 3 | 9 | 9 | |
| 6 | Change in work intensity | 4 | 5 | 3 | 1 | 3 | 5 | Alt. 1 and 5 provide frequent changes in work intensity. |
| | | S | 20 | 12 | 4 | 12 | 20 | |
| 7 | Safety and ergonomic conditions | 4 | 5 | 5 | 3 | 1 | 3 | The operators are isolated from the machine area, in alt. 1, and 2. |
| | | S | 20 | 20 | 12 | 4 | 12 | |
| | Total score | | 205 | 201 | 115 | 57 | 127 | |

W= weight S= score for criterion (marked)

# List of symbols

| | |
|---|---|
| $\alpha_j$ | The mass of a fraction compared to the total mass of the shredding part |
| $\delta$ | System availability |
| $C$ | Total recovery costs |
| $C_{as}$ | Assembly costs |
| $C_c$ | Price of the replaced component |
| $C_d$ | Cost of disposal |
| $C_{da}$ | Disassembly costs |
| $C_{dim,com}$ | Compressor's dismantling cost |
| $C_{dis}$ | Disassembly costs to replace a component |
| $C_{dis,ax}$ | Cost for the disassembly of the remaining axis' fractions |
| $C_{dis,\ co}$ | Cost for the disassembly of the remaining coil's fractions |
| $C_{dis,com}$ | Compressor's disassembly cost |
| $C_{dis,j}$ | Disassembly costs of component j |
| $C_{dis,rest}$ | Cost for the disassembly of the remaining compressor's fractions |
| $C_{dis,\ rot}$ | Cost for the disassembly of the remaining rotor's fractions |
| $C_{dm}$ | Dismantling costs |
| $C_{dm,\ ax}$ | Cost for the dismantling of the remaining axis' fractions |
| $C_{dm,\ co}$ | Cost for the dismantling of the remaining coil's fractions |
| $C_{dm,j}$ | Dismantling costs of component j |
| $C_{dm,\ rest}$ | Cost for the dismantling of the remaining compressor's fractions |
| $C_{dm,\ rot}$ | Cost for the dismantling of the remaining rotor's fractions |
| $C_{dp}$ | Cost for disposal of the good without recovery |
| $C_{dp,a}$ | Cost for disposal of the remaining part of the good after recovery the valuable fractions (decreasing the negative revenues) |
| $C_{fr}$ | Freon's processing cost |
| $C_m$ | Miscellaneous costs |
| $C_r$ | Cost of items that must be replaced by new ones |
| $C_{rec}$ | Total recovery costs |
| $C_s$ | Cost of service items |
| $C_{sep,j}$ | Separation cost of a material fraction of the shredded part |
| $C_{shr}$ | Operation cost of the shredder |
| $C_{shr,\ co}$ | Cost for the shredding of the remaining coil's fractions |
| $C_{shr,rest}$ | Cost for the dismantling of the remaining compressor's fractions |
| $C_t$ | Cost of use of any special tools or equipment per service task |
| $C_v$ | Value of reclaimed parts |
| $C_{vm}$ | Maximum reclaimed value |
| $D$ | Working days per year |
| $D_i$ | Proportion of discarded materials |
| $I_r$ | Recycling efficiency |
| $I_s$ | Design for service index |
| $k$ | Number of material fractions |

| | |
|---|---|
| $k_h$ | Working hours per day |
| $k_{sh}$ | Number of shifts |
| $L$ | Useful life time |
| $L_l$ | Appropriate labour rate |
| $M$ | Mass of the shredding part of the good (subassembly) |
| $m$ | Number of valuable components/ mass of used material |
| $m_{al}$ | Aluminum material's revenue |
| $m_{cab}$ | Cable's mass |
| $m_{fe}$ | Ferrous material's revenue |
| $m_{fr}$ | Freon's mass |
| $m_{gl}$ | Glass's mass |
| $m_{pl}$ | Mass of the plastic fraction |
| $m_r$ | Mass of the rubber fraction |
| $N$ | Theoretical number of alternatives |
| $n$ | Number of components |
| $P$ | Net result (profit) |
| $P_a$ | Annual production rate |
| $P_{max}$ | Maximum profit |
| $P_{dis}$ | Profit from disassembling |
| $P_{dm1}$ | Profit from dismantling |
| $P_{dm2}$ | Profit from dismantling |
| $P_{ref}$ | Total refrigerator's recovery profit |
| $P_{shr}$ | Profit from shredding |
| $R$ | Total revenues from recovery |
| $R_{ax}$ | Axis' revenue |
| $R_{case}$ | Case's revenue |
| $R_{co}$ | Coil's revenue |
| $R_{com}$ | Compressor's revenue |
| $R_{com,rest}$ | Revenue of the remaining compressor's materials |
| $R_{fr}$ | Freon's revenue |
| $R_j$ | Revenue of component j |
| $R_{ref}$ | Refrigerator's revenues |
| $R_{rot}$ | Rotor's revenue |
| $r$ | Proportion of recycled materials |
| $r_{al}$ | Aluminum material's revenue per kilogram |
| $r_{fe}$ | Revenues from the ferrous fraction per mass unit |
| $r_{fr}$ | Freon's revenue per kilogram |
| $r_{gl}$ | Glass's revenue per kilogram |
| $r_{min}$ | Required minimum proportion of recycled materials |
| $r_{pl}$ | Revenues of the plastic fraction per mass unit |
| $r_r$ | Revenues from the rubber fraction per mass unit |
| Re | Percentage of recycled materials |
| Sec | Proportion of materials which is used in the secondary market |
| $t$ | Required cycle time |
| $T$ | Period of usage of a product |
| $T_d$ | Disassembly time |

| | |
|---|---|
| $T_a$ | Reassembly time |
| $T_g$ | Time of diagnosis or fault verification |
| $T_p$ | Consumer time in a primary market |
| $T_s$ | Consumer time in a secondary market |
| V | Money value of a discarded good before repair |
| $V_i$ | Percentage of virgin materials |
| $V_{pr}$ | Money value of the good after repair |

# List of abbreviations

| | |
|---|---|
| ABS | Acrylonitrile-Butadiene-Styrene |
| ARIC | Appliances Recycling Information Centre |
| BOVAG | Automobile Service Organization |
| BS | Butadiene-Styrene |
| CFC | Chlorofluorcarbon |
| DFA | Design for Assembly |
| DFD | Design for Disassembly |
| DFMA | Design for Manufacturing and Assembly |
| DFS | Design for Serviceability |
| DM | Deutsche Mark (German currency) |
| EZ | Dutch Ministry of Economic Affairs |
| FMEA | Failure Mode and Effects Analysis |
| PCB | Printed Circuit Board |
| PDM | Product Design Merit |
| PUR | Polyurethane |
| PVC | Polychlorinated Biphenyl |
| QFD | Quality Function Deployment |
| RWE | Recycling Company |
| STIBA | Dutch Automobiles Recycle Organization |
| VDI | Union of German Engineers |
| VROM | Dutch Ministry of Social Health, Development and Environment |

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**About the author**

Kiril Penev was born in Sofia, Bulgaria. From 1978 to 1982 he studied at the Mathematics gymnasium in Sofia where he graduated with distinction. From 1982 to 1984 he did obligatory military service. In September 1984 he began his study in the Faculty of Mechanical Engineering at Technical University of Sofia. The final thesis deals with the development of an assembly line. In July 1989 he graduated at the Department of the Automation of Discrete Production and received his M.Sc. degree in Mechanical Engineering. In 1990 he worked one year as a designer in the Machine Building Institute in Sofia. Then he obtained a temporary position at the Technical University of Delft as a researcher in the Laboratory of Robotics and Flexible Automation. From 1991 until 1993, he followed the two-year post graduate degree course "Computer Aided Design and Manufacturing of Discrete Products" at the Institute for Continuing Education at Eindhoven University of Technology and obtained the qualification Registered Technical Designer. During the second year, he worked as a process engineer at NedCar Production BV, the Dutch manufacturer of cars, where he took part in development and implementation of robotized assembly lines. From September 1993 until December 1995 he was involved in Ph.D. research in the field of disassembly and recovery of discarded goods, which was carried out at Eindhoven University of Technology, Manufacturing Technology Group, and in co-operation with various industrial firms.

Since January, 1996 he has been working at Philips BV, Centre for Manufacturing Technology Division, Production Systems Department, in Eindhoven.

# STELLINGEN

behorende bij het proefschrift

# Design of Disassembly Systems:

**a systematic approach**

van

Kiril Penev

maart 1996

I

If in the future the main goal is still focussed on economic growth, while recovery is neglected as an option to preserve the planet, destruction of our modern society will be observed. (Source: Chapter 1 of this dissertation)

II

A systematic design approach can not replace (substitute) intuition and creativity which are unique human elements. However, such an approach can help designers to avoid important design aspects from being neglected. (Source: Chapter 3 of this dissertation)

III

The technological developments within the manufacturing industry are not followed adequately by the recycling industry. (Source: Chapter 4 of this dissertation)

IV

The development and implementation of disassembly systems is the first and necessary step to reduce the environmental impact of discarded goods. (Source: Chapter 5 of this dissertation)

V

Recovery activities may be in contradiction with sustainable development.

VI

Freedom is a system based on courage.

VII

Every man is a creature of the age in which he lives; very few are able to raise themselves above the ideas of the time. (Source: Voltaire)

VIII

Science is nothing but trained and organized common sense. (Source: Th.Huxley)

IX

Practice is the mother of science.

X

A problem well stated is a problem half solved.

XI

The higher you go, the windier it gets.

XII

The "Why", "What", "How", "Where", "When" and "For whom" one needs to produce are the oldest economic questions. Unfortunately, some people who are making the change from a centrally planned to a market economy do not consider these important issues.