Keynote Papers

A Key Issue in Product Life Cycle: Disassembly

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Abstract

Incoming environmental legislation is expected to impose recycling activities on industrial and consumer product manufacturers. Disassembly of used products is needed in order to make recycling economically viable in the current state of the art of reprocessing technology, thus avoiding the future high disposal costs. This paper gives an overview of disassembly research at universities, research centers and industrial companies, pointing out ongoing topics and trends for future activities. Among them, major attention has been paid to basic technological development, product design (design for disassembly), process design (selection of disassembly strategy and automation level) and system design (configuration of manual and automated disassembly facilities, design of disassembly tools). It is also shown how the emerging life cycle concept can be fully exploited to develop suitable ways of dealing with information related to environmental protection and resource optimization. A result of the survey is that further development on disassembly of existing products (technology, planning at process and system level) is needed to allow future products to be designed with recycling considerations in mind.

Key words: Assembly, Disassembly, Recycling

1. Introduction

Industrial countries are beginning to face one of the consequences of the rapid development of the last decades. Wide diffusion of consumer goods and shortening of product lifetime have given rise to an increasing quantity of used products being discarded. Situation in Germany, where consistent data about scrap rates are available (Fig.1 [59]), shows that the main problems concern cars (scrap volumes more than doubled from 1960 to 1990 [49]), household appliances and consumer electronic goods. A future burden will come from computers, due to their rapid obsolescence rate.

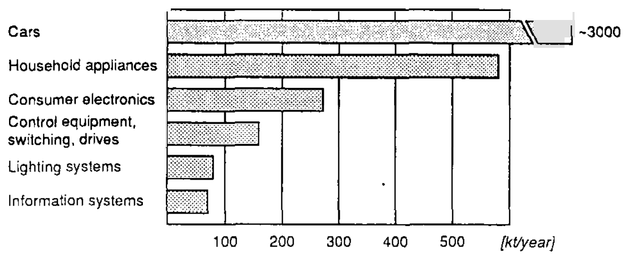

Fig.1: Yearly scrap rates for consumer products in Germany [59]

The most evident effect is that landfill capacity is being used up (half of US sites will be shut down in the next 3 years [25]). As an effect of incoming regulations, like the proposed EC Landfill Directive [97] requiring improved standards of preparation and operation, the related costs are exploding (from 20 to 600 DM/t in Germany during the last 5 years [67, 125], from 100 to 600-1000 $/t in USA in the near future [49]). Then, disposal costs will be added to the total cost of products, with special consequences for bulky equipment such as [70, 97] cars, kitchen appliances (washing machines, refrigerators), office equipment (computers and large photocopiers), telecommunications equipment (telephones and fax machines) and consumer electronic devices (TV sets, video recorders, microwaves).
To face environmental problems, regulations inspired by the "polluter pays principle" are emerging. Germany is leading this process, due to its high amount of scrap relative to the surface available for dumping. The Decree on Electronic Waste (active from 1994 [42]) and the Decree on Used Cars (under development [98]) will force manufacturers to reclaim waste, to reuse the recyclable fraction and to dispose of the residue. German experience will be a reference for the EC environmental legislation, which is expected to be implemented by 1996 [97]. Similar initiatives have been taken in USA and Japan.
These regulations are forcing manufacturers to undertake efforts on *recycling*. Recycling means recovering materials or components of a used product in order to make them available for new products. This means "closing the loop" of the product at different stages of its life cycle [104]:
- during production, e.g. residues from sheet metal cutting and injection molding (companies refer to it when stating that their products contain a certain fraction of recycled material);
- during product usage, typically as an effect of repairing;
- after product usage, the most promising form of recycling for industrial and consumer products.

During all these loops, different kinds of recycling are possible, as both shape and function of the original product can be kept or not for future tasks [104]. Examples for the different options are given in Fig.2.

Loop	Form of recycling	Original product	Recycled product
Recycling during product usage	Same shape, same function (*reusing*)	Bottle	Refilled bottle
		TV set	Repaired TV set
		Car tire	Remolded car tire
	Same shape, different function (using on)	Milk bottle	Flower vase
		Shopping bag	Waste bag
		Old tire	Ship fender
Recycling after product usage / Recycling of production scrap	Different shape, same function (*reutilization*)	Glass bottle	Bottle from recycled glass
		Aluminium can	Can from recycled aluminium
		Sheet metal scrap	Sheet metal
	Different shape, different function (*utilizing on*)	Glass window	Bottle from recycled glass
		Aluminium cans	Aluminium window frame
		Sheet metal scrap	Wires

Fig.2: Different forms of recycling [104]

Recycling is gaining increasing attention from governments. Emerging policies, both encouraging and restrictive, include [10, 115]:
- incentives for manufacturers who use recycled materials when these are not the most economical choice;
- taxes on the use of virgin materials, as well as deposit fees to be returned when those materials are recycled;
- systems to measure recyclability of products, so that manufacturers could be charged with penalties if they do not meet specific recyclability standards.

One intangible benefit arising from recycling is a "green" image. Many governments now have official ecolabelling schemes, intended to inform customers of environmentally friendly products. The EC is oriented on assigning ecolabels according to an assessment matrix based on the nature of waste created by products [97].
These initiatives are stimulating industrial companies to start activities in the recycling field. Some work groups have been established by organizations of manufacturers, especially in the automotive sector. Examples are the Post-use Vehicle Solutions Subcommittee of Japanese Automobile Manufacturers Association (JAMA) [10], the ACORD recycling project launched in the UK by the Automotive Group [86] and the PRAVDA project, started by the German Association of Vehicle Manufacturers (VDA) [24, 26]. When a complete legislative scenario is available, manufacturers will be even more encouraged to move into recycling business.
While new products can be "designed for recycling", existing products have to be recycled according to available technologies. Reuse of parts and subassemblies and material recycling are the two possible choices.
Significant benefits would result from reusing whole parts or subassemblies. For example, feasibility studies on electromechanical products have resulted in an average 30% reduction in the final cost by using recycled parts [91]. However, it is not easy to find a market for reconditioned parts or functional groups. As a consequence, only material recovery is practical at present.
Remelting is a well-known way of recycling metal parts. Savings from alloys produced by metal scrap are relevant: the best example is aluminium, whose production energy can be reduced by ten times as compared to the primary process (Fig.3) [28, 72].

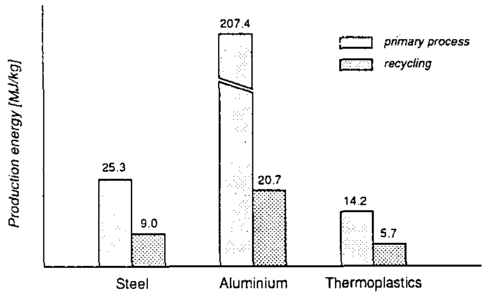

Fig.3: Energy balance for some engineering materials [28]

Among non-metallic materials, plastics have the largest volumes [30], but their recycling is still difficult for the following reasons:
- Too many different materials are used, each designed for a specific function. Variety of plastics should be reduced through standardization on selected types [124]. This will be easier in the future, as properties of plastic materials improve and individual types become more versatile;
- Separation is often difficult due to structural adhesives or metallic inserts [25]. Moreover, it is difficult to recognize different materials for correct separation.

While standardization is still submitted to initiatives of individual manufacturers, ease of separation has been considered by standardization organizations and by the plastics industry. A number of official standards (SAE J1344, ISO 1043, VDA 260, ASTM D 1972 [10, 61]), along with corporate ones [1], provide an aid in recycling automotive materials by a coding system for plastic parts. The codes allow dismantlers to classify different materials by giving them information about common names, standard symbols and trade marks. In particular, the SAE code has been accepted by the Society of Plastics Industry (SPI) and by most US automakers. Since the different standards are only partially compatible, a single code needs to be accepted worldwide in the near future.
Similar problems affect recycling of rubber and glass, which are also promising sources of secondary materials [27, 41, 79, 94].
Electronic materials (gallium, germanium, silicon, indium) as well as ceramics can be profitably recycled because of their high production cost [87]. Many industrial processes have been proposed for extracting these valuable elements from

components on PCBs [97]. Another critical issue is electrolytical purification of copper, a valuable material which can be an impurity for steelmaking [97]. Lead from car batteries can also be recycled [29], as it is the case for platinum and rhodium from catalytic converters [107].
Composites, on the contrary, are nearly unrecyclable for at least three reasons [49]:
- original constituent elements are difficult to restore for separate reuse;
- composites are often designed according to special performance specifications, which may not be required by new applications;
- the volume of composites entering the recycle stream is usually too small to justify the necessary recycling infrastructure.

Fig.4 lists some of the techniques currently available for plastics recycling [7, 10, 13, 25, 26, 42, 56, 57, 71, 74, 89, 94, 107, 118, 119].

Materials	Processes
Thermoplastics (polypropylene, nylon, RIM, polystyrene, TPU/ABS blend)	- Paint removal (filtration, solvent dissolution, water blasting, grinding) - Regrinding for remolding
Thermosets (SMC, BMC, polyurethane RIM and foams)	- Energy recovery (fluidized bed, rotary kiln combustion) - Pyrolysis - Glycolysis
Glass reinforced (Thermoplastic or thermoset substrate, fiber or mat reinforce)	- Direct recycling (compression, injection, extrusion) - Substrate grinding - Incineration with glass recovery - Oxidation and solvent dissolution with reinforce recovery
Mixed	- Decomposing catalysis - Depolymerization (hydrolysis, alcoholysis)

Fig.4: Recycling techniques for plastics

The technological developments within the manufacturing industry have not been paralleled by the recycling industry. There is a lack of technologies to handle the very complex products that are being disposed of today. Thus, material recycling is currently limited to ferrous and some non ferrous metals [104], which are usually recovered from cars and kitchen appliances by a *shredding* process followed by several stages of sorting. In shredders, scrap is compressed and fed into a drum, where it is ripped apart by a set of rotating hammers, until it is small enough to drop out of an output grid. Then, lightweight materials like textiles and some plastics are separated in an air tunnel. The next step is a magnetic separation of steel and other ferrous metals. What is left over are heavy, non magnetic materials like glass, rubber and some plastics. The magnetic fraction is often subject to hand picking of valuable non ferrous metals, that may have been transported by the ferrous fraction. The light fraction and the non magnetic heavy fraction, an important part of total weight (plastics, aluminium, composites), cannot be separated further and have to be dumped [104].
One of the drawbacks of the shredding process is that it cuts the product at random lines, leading to fractions containing more than one material. If mixed metal fractions cannot be identified and sorted out, they tend to produce unwanted alloys during later metallurgical processes. Reducing the grain size of the shredding process would lead to a smaller fraction of mixed materials, but would require greater shredding, identification and separation efforts.
These considerations clearly show that only *disassembly* of products can allow complete material recycling, along with possible part and subassembly reuse.

2. The disassembly problem

A proper way to treat products for recycling could include [104]:
- draining all fluid components (typically, from a car);
- disassembling all materials and components that cannot be recovered in sufficient purity after shredding;
- shredding and sorting the remaining fraction;
- disposal of non-recyclable materials (*fluff*).

Evident benefits could derive from this practice [59, 124]:
- more high quality components can be refurbished and reused;
- metallic parts can be separated better, reducing contamination and enhancing their recycled value;
- disassembled parts made of other materials (plastics, glass, wood, etc.) do not become part of the fluff, reducing disposal problems, and can be reprocessed.

Some obstacles make disassembly difficult for today's manufactured product [104]. First, it is difficult to gain all the information necessary to plan the disassembly. Parts of the product might have been modified during repair, and wear can make joining elements difficult to remove. But the main point is that many consumer products are not designed for ease of disassembly. In particular [80]:
- product structure is optimized on the basis of functional and assembly requirements, resulting in a lot of unwanted disassembly steps;
- joining methods are chosen for simple assembly and safe joining; unloosenable joinings and difficult access to joining elements can occur;
- materials are chosen so as to be economical and of optimum performance; this means a lot of different, often unrecyclable, materials, with high disassembly and sorting costs.

As a result, disassembly today requires highly skilled workers, which is not economically feasible for industrial practice [104].
Fig.5 lists the main criteria that can be applied for selecting parts and subassemblies to be recovered through disassembly [96].

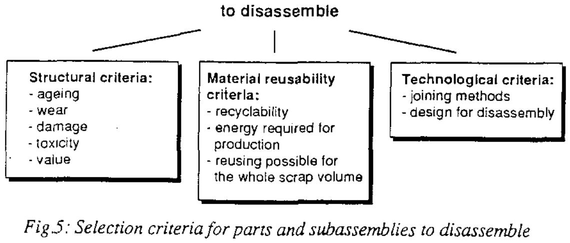

Fig.5: Selection criteria for parts and subassemblies to disassemble

Disassembly techniques are quite different among automotive, electromechanical and electronic products. A classification of them can be done according to aims and effects of the process.
Aim - Disassembly can be justified by the level of recycling it allows. The following options are applicable [80]:
- reuse of parts or subassemblies, for functional units with high manufacturing costs, with long innovation cycles and long lifetime;
- special processing of subassemblies (e.g. further separation for reuse of cables, PCB and electronic components), when product units are in the form of complex mixtures of materials, with short innovation cycles or short lifetime;
- material recycling, when single parts have low production costs, large volumes or high material costs, short innovation cycles or short lifetime.

Effect - Different disassembly techniques can result in original shape of components being saved or not. Accordingly, disassembly can be classified as [80]:
- non-destructive, involving no part demolition (loosening of screws, detaching, pressing out);
- partially destructive, with demolition of cheap parts (chip removal of joints, torch cutting, high pressure water cutting, laser cutting);
- completely destructive, with uncontrolled destruction of product structure (shredding, milling).

Fig.6 shows a matching between the two classification criteria [80].

category of disassembly	disassembly techniques for		
	subassembly reusing	subassembly special processing	material recycling
disassembly from the product	- non-destructive - partially destructive	- non-destructive - partially destructive	- any
disassembly of removed unit into parts	- non-destructive	- dependant on special processing	- unnecessary

Fig.6: Selection of disassembly techniques [80]

In addition to aiding disposal, efficient disassembly is also of benefit for servicing and repair during product lifetime, as well as for remanufacturing (for robots and machine tools). From a maintenance viewpoint, fastening methods should be completely reversible, because dismantling cannot be destructive [78, 88, 108, 124].

3. Life cycle design

Typically, development of new products starts on the basis of a set of specifications, based on the assessment of market needs. Then, selection of technical solutions is based on company policy, product and manufacturing properties, cost. Rarely are environmental issues considered during this process. For example, disposal costs are hidden, paid by the consumers through taxes, and not individually allocated to products. If they were, it would draw the company's attention to environmental concerns. In the future, however, environmental legislation will force a change in design, requiring that products are economically sound to produce, distribute, use and dispose of [14, 15].
A new approach, called *life-cycle design*, is emerging to effectively manage these additional concerns. This concept is an evolution of concurrent engineering, and consists in all cycle phases (needs recognition, development, production, distribution, usage, and including disposal or recycling) being considered simultaneously from the conceptual product design stage through the detailed design stage (Fig.7) [14].

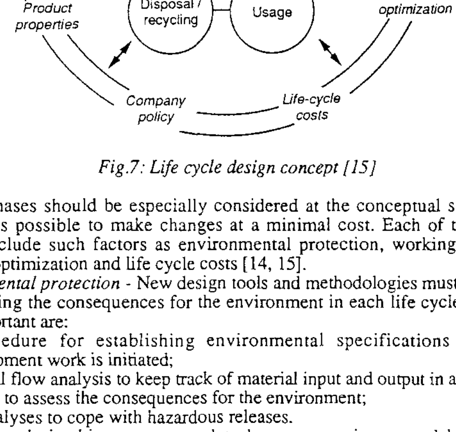

Fig.7: Life cycle design concept [15]

All the phases should be especially considered at the conceptual stage, during which it is possible to make changes at a minimal cost. Each of these phases should include such factors as environmental protection, working conditions, resource optimization and life cycle costs [14, 15].
Environmental protection - New design tools and methodologies must be supplied for assessing the consequences for the environment in each life cycle phase. The most important are:
- a procedure for establishing environmental specifications before the development work is initiated;
- material flow analysis to keep track of material input and output in all phases;
- models to assess the consequences for the environment;
- risk analyses to cope with hazardous releases.

Valuable tools in this respect are data bases on environmental behaviour of chemical materials, such as ELDIN (Environmental Chemical Data Information Network), developed at the Technical University of Denmark and RTEC (Registry of Toxic Effects of Chemical Substances) of the US National Institute for Occupational Safety and Health.

Working conditions - Many recent occupational health issues could have been avoided if production, usage and disposal had been considered at the design stage. Although it is not easy to evaluate the consequences of possible harmful emissions (noise, vibration, heat, electromagnetic fields, etc.) and their concentration for each life cycle phase, the mere awareness of these potential problems could lead to better solutions, as design groups do not wish to take responsibility for creating harmful working conditions.

Resource optimization - Energy and material must be used efficiently not only in production (many companies are working on this topic), but also in the other life cycle phases, including distribution, disposal and recycling.

Life cycle costs - Product costs in industry typically cover only design, production and distribution. In the future, however, it will be necessary to develop models that describe all the life cycle costs (including disposal and recycling costs) so that it could be possible to compare different product alternatives. As outlined in Fig.8, life cycle costs are shared among manufacturing companies, users and society. Distribution of life cycle costs can vary considerably from product to product.

Life cycle phase	Company costs	User costs	Society costs
Need	Market recognition		
Design	Development		
Production	Materials, energy, facilities, wages and salaries		Waste, pollution and health damages
Distribution	Transportation, storage, waste	Transportation, storage	Waste, pollution, packings and health damages
Use	Warranty service	Energy, materials, maintenance	Waste, pollution and health damages
Disposal		Disposal dues	Waste handling, disposal, health damages, pollution
Recycling		Recycling dues	Waste, pollution and health damages

Fig.8: Life cycle costs [15]

In addition to extending the time horizon taken into account in product design, companies have to consider the environmental impact of the processes and of the logistic support organization. Therefore, an integrated approach is desired which considers these three elements during the whole life cycle (Fig.9) [104].

In general, each life cycle phase is implemented through a system, which has its own life cycle phases to be considered. A global view of product life cycle can also help to understand when product quality is generated, used and consumed, in order to set up adequate quality management strategies (Fig.10 [65]).

Interest of manufacturing companies on life cycle design is increasing considerably: some in Europe and USA (Bayer, DuPont, Henkel, IBM, Polaroid) have created environmentally related positions or task forces, responsible for environmental audit processes and training of designers [15]. A new industrial culture is arising, based on *sustainable production*. It means that products are designed, produced, distributed, used and disposed of with minimal environmental and occupational health damages, and with minimal use of resources (materials and energy).

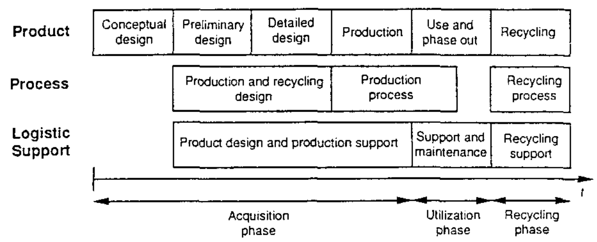

Fig.9: Extension of life cycle concept [15]

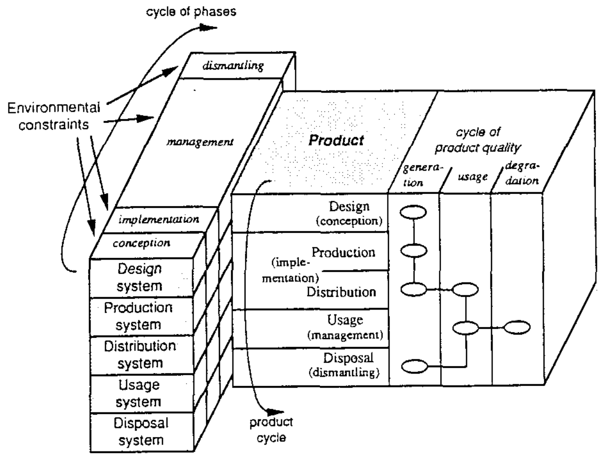

Fig.10: A global view of product life cycle and quality issues [65]

In the future many research efforts will focus on the problems related to sustainable industrial products. To stimulate this it was decided at 1992 CIRP General Assembly to form a Life Cycle Working Group where researchers and industrialists can present results and plan new joint activities [17]. At IPU, Technical University of Denmark, where the life cycle design concept was first identified, a Life Cycle Center has been established with researchers and consultants working on three main technology areas [17]:

- life cycle strategies, economy and control (assessment of life cycle costs, business concept and activities);
- process and production engineering (environmental and resource oriented design of products);
- environmental and resource technologies (clean production, legislation requirements).

The Life Cycle Center is leading a cooperative project among several Danish partners on Environmental Design of Industrial Products (EDIP) [16, 17, 66]. The aim of the project is to develop and implement a method for life cycle design of new products. Availability of guidelines and software tools for product development would be of great benefit, since most environmental, occupational health and resource loads in the product life cycle are determined in the early phases of product design. The core of the methodology being developed is an assessment and evaluation method, which performs a quantitative comparison of the product under consideration with a reference product. Two kinds of reference products are relevant:

- an equivalent product existing on the market (functional reference);
- an aggregate of products chosen to represent the technological content of the new product (technological reference).

The comparison is based on data about the environmental effects of the various life cycle phases, collected in an initial inventory phase (Fig.11a) and grouped into effect categories (on global, regional and local scale). An example of graphical representation of the comparison is shown in Fig.11b.

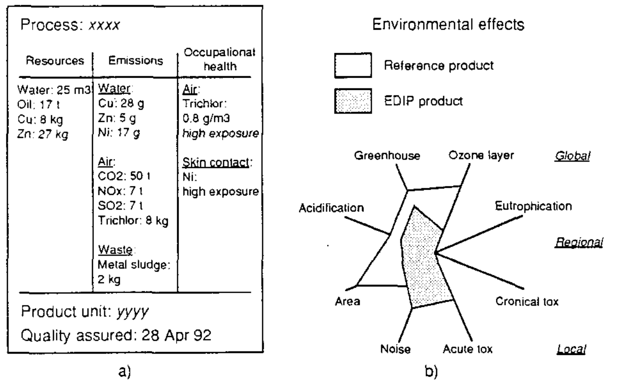

Fig.11: EDIP assessment/evaluation method [17]

Work is also being done at Daimler-Benz [50, 122] on life cycle design support to product development. The approach is based on an ecological balance of the product, where all relevant factors (production processes of materials, product, tools, equipment, machinery and energy) are studied to get values for environmental loads classified into emissions, waste water and dump.

Research at IPK, Technical University of Berlin, is focused on an environmentally oriented decision support system whose main feature is a simulation of the effects of a product during its life cycle [73].

A key problem to be solved in order to perform reliable economic analyses on new products is life cycle cost assessment. It is not clear, in fact, how environmental data have to be turned into information usable in accounting procedures. Tipnis [110, 111, 112] distinguishes between *penalty costs* resulting from the environmental risks while the product is being manufactured, stored, used, disposed or recycled, and *opportunity costs*, which allow advantageous positions to be accomplished by environmental and ecological responsiveness. Such costs have to be taken into consideration together with actual costs in order to define the target cost of the product (difference between competitive price and desired profit):

$$\textit{actual costs} + \textit{penalty costs} - \textit{opportunity costs} \leq \textit{target cost}$$

As pointed out at CIM Institute, Cranfield [93], an assessment of life cycle costs can help to recognize long term economic benefits of products designed for recycling. These benefits, represented by a higher *post-purchase value*, might have been hidden by a higher *pre-purchase cost*. Recyclability should instead be measured by a *total life cycle cost*:

$$\textit{total life cycle cost} = \textit{pre-purchase cost} - \textit{post-purchase value}$$

Pre-purchase cost is given by material, manufacture and assembly costs. Post-purchase value can be obtained by subtracting all recycling costs, such as recovery and logistic costs (transport, storage, customer incentive to return the product), disassembly cost and landfill cost for the non-recyclable fraction, to the value recovered by recovering subassemblies, parts and materials.

A good recyclability index can be the *life cycle profit*. If a fraction r of volume sold is returned to manufacturer by customers, yearly life cycle profit can be calculated as

$$\textit{LC profit} = (\textit{pre-purchase cost} - r \cdot \textit{post-purchase value}) \cdot \textit{volume}$$

volume sold can be higher for recyclable products due to the favourable market acceptance for products labeled as "green".

Assessment of life cycle costs is also studied at the Industrial and Manufacturing Engineering Department of the University of Rhode Island [90] and at the Swiss Federal Institute of Technology (ETH), Zurich [127].

An research group established at the Mechanical Engineering Laboratory (MEL) of MITI, Japan, is working on an organizational structure for the implementation of life cycle design concepts in manufacturing companies. The structure, called *Ecofactory* and depicted in Fig.12, distributes the work between a production system, responsible for designing and creating environmentally safe products, and a restoration system, responsible for disassembly, recycling and returning materials and reusable units to the production system [3].

When a comprehensive methodology for life cycle design of products is available, designers will be able to design new products with knowledge of the environmental effects at any design decision. At present, the concept is used as a guide for both disassembly of existing products and design for disassembly of new products.

According to automotive and plastics manufacturers [2, 35, 36], selection of parts and subassemblies to be removed from used products have to be guided by two life-cycle related concepts:

- *quantity balance*: a secondary application has to be found for the whole quantity of material coming from disposed products; recycling can be planned on the same product or in different applications (e.g. packaging or civil engineering for plastics);
- *cascade*: recycling of a material on the original application can be an environmentally incorrect choice (recycling polypropylene from bumpers to make new bumpers requires adding additives to the material to improve its performance, but additive production produces new environmental pollution); the better choice can often be to find low performance applications for a second and possibly a third life of the material (e.g. bumpers to air hoses and later to floor mat substrates).

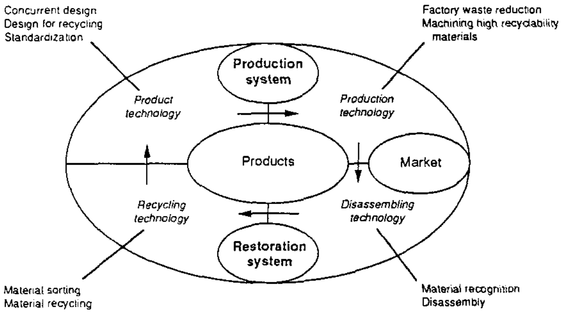

Fig.12: Ecofactory concept [3]

For new products, Dow Chemical has proposed a methodology, called *Ecobalance*, to evaluate how using a material to build a product can affect the global energy balance. Ecobalance calculates the global energy consumption in material production, taking the volume of parts into account. So, material selection decisions can be taken according to the total energy put into a specific part [28, 54].
FIAT is currently applying a similar method for selecting materials to be used in automotive construction, according to parameters concerning energy balance (energy consumption in production, use, dismantling and reprocessing, energy recovery) and resource utilization (volumes, scrap, separation, degradation) [95].
IBM has launched a life cycle design program, called "Environmental Impact Assessment" (EIA), aimed to provide itself and customers with environmental information on the product, at all stages of product life, to safely and properly handle the product and its wastes. Results of the program include methodologies for analysis of product chemical emissions, as a support for *source reduction* (design of products and processes in a manner that they will not result in the generation of hazardous waste) [4].

4. Current activities

Current research and implementation activities on disassembly can be grouped into three main areas:

- design of product for ease of disassembly;
- design of disassembly processes;
- design and implementation of disassembly systems.

4.1. Product design

Since today products are not designed with life cycle considerations in mind, disassembly is not yet economical for large scale application. So, a key issue is to learn from industrial experiences on dismantling how to design future products which would be suitable for efficient and complete disassembly.
Considerable research effort is beginning to be paid to *design for disassembly* of automotive, electromechanical, electronic and consumer products. Due to the high variability in product structure and recycling constraints, design rules can vary from one sector to another.
Activity in this field can be classified into:

- formulation of design criteria, to be applied by designers during conceptual and detailed design;
- development of evaluation methods and software tools for economic analysis of alternative design decisions.

An important contribution to the formulation of design for disassembly rules has been given, among others, by research groups at WZL, Technical University of Aachen [44, 45, 58], IPA, Fraunhofer Institute, Stuttgart [69, 117], IWF, Technical University of Berlin [104, 105], Manchester Polytechnic [106] and Siemens [39, 40], as well as by several industrial companies in the US (Dow, GE Plastics, Xerox, DEC) [77, 90], and in Germany (Loewe, Bayer) [11, 97]. The topic is also treated in German standard VDI Richtlinie 2243 [12].
Early studies have first pointed out the differences between design for disassembly and design for assembly, a practice for which consistent and applicable guidelines and methodologies have already been proposed [24]. For example, some kinds of joining methods are well-suited for assembly, but are difficult to remove (rivets, snap-fits, spot welds).
Design for disassembly criteria can be classified according to the benefits they offer: the main advantages arising from a disassembly-oriented product design are:

- less work needed to recover recyclable parts and materials;
- more uniformity and predictability of product configuration;
- simple and fast disconnecting operations;
- easy manual or automated handling of removed parts;
- easy separation and post-treatment of recovered materials and residuals;
- reduction of product variability.

A list of the generally accepted design rules is given in Fig.13.

Less disassembly work
During product design it should already be clear which parts and subassemblies will have to be disassembled. The best candidates are:

- parts made of materials which can create problems in reprocessing (e.g. copper for steel remelting and metal inserts for thermoplastic regrinding and remolding);
- parts made of valuable materials, whose recovery is economically viable regardless of the small quantity (such as some electronic components on PCBs);
- directly reusable parts or subassemblies.

Product structure should be prepared to allow dismantling of those parts with the minimum effort. The following suggestions are applicable:

Benefits	Criteria
Less disassembly work	- Combine elements - Limit material variability - Use compatible materials - Group harmful materials into subassemblies - Provide easy access for harmful, valuable and reusable parts
Predictable product configuration	- Avoid ageing and corrosive material combination - Protect subassemblies against soiling and corrosion
Easy disassembly	- Accessible drainage points - Use fasteners easy to remove or destroy - Minimize number of fasteners - Use the same fasteners for many parts - Provide easy access to disjoining, fracture or cutting points - Avoid multiple directions and complex movements for disassembly - Set center-elements on a base part - Avoid metal inserts in plastic parts
Easy handling	- Leave surface available for grasping - Avoid non-rigid parts - Enclose poisonous substances in sealed units
Easy separation	- Avoid secondary finishing (painting, coating, plating etc.) - Provide marking or different colours for materials to separate - Avoid parts and materials likely to damage machinery (shredder)
Variability reduction	- Use standard subassemblies and parts - Minimize number of fastener types

Fig.13: Design for disassembly criteria

Parts consolidation - This concept involves the reduction of the number of the components of a product [77]. The simplified design contributes to cut disassembly time, because fewer parts have to be removed. Engineering plastics are best suited for maximum integration, through their ability to form complicated parts [2, 23].
Material variability limitation - The number of materials used in a product should be kept to a minimum. A price to be paid could be "overdesigning" material in some parts in order to match other parts with tighter performance requirements. For instance, if a computer casing is made of polycarbonate because of impact-resistance requirements, but an internal component requires less expensive ABS, replacing ABS with polycarbonate can reduce the number of different materials to be separated [77]. Overdesign increases the initial cost of the product, but may lead to a lower life cycle cost [2]. The plastics industry is working at a standardization of the grades applied in the automotive sector. Moreover, Bayer, BASF and Himont, among others, produce recycled polymers from automotive and electromechanical scrap.
Material compatibility - An alternative choice is to accept different materials, provided that they can be recycled together. In the previous example, one can also utilize both polycarbonate and ABS in separate parts, with the aim of recycling them as one material (a PC-ABS blend). Necessary conditions are the compatibility of the two materials (Fig.14 [96]) and the existence of a market for the recycled alloy [77].
Clustering - Parts to be removed, especially should be grouped into subassemblies for fast disassembly.
Easy access for parts to be removed - Harmful, valuable and reusable parts should be easily accessible for removal, in order to minimize unnecessary disassembly of non-recyclable parts.[104].

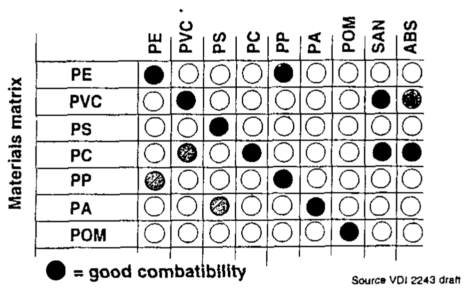

Fig.14: Compatibility of engineering plastics [96]

Predictable product configuration
An obstacle to disassembly is the uncertainty in product configuration, due to repairs, contamination and corrosion. These problems can increase the operating time in manual assembly, and make automated disassembly completely impossible. Possible remedies are:
Careful material combination - Combination of materials giving rise to ageing or corrosion should be avoided [69].
Protection against contamination - Parts and subassemblies to be removed should be protected against soiling and corrosion [69].

Easy disassembly
As previously discussed, disassembly can be done by simple "reverse assembly" (screwing out or snapping apart components and fasteners) or by "brute force", in a partially or totally destructive process [77]. A number of design rules can be

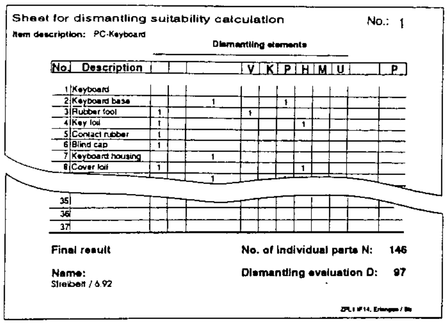

Fig.19: Dismantling suitability evaluation [96]

Research at IWF, Berlin, focuses on the development of a user friendly methodology to evaluate costs and benefits of disassembly, in order to compare given alternatives with respect to their ease of disassembly [102, 103].
Activity is reported by VDI, aiming at supporting designers in analyzing different fastening methods according to possible disassembly solutions for each of them [20, 21, 22, 75, 121, 123].

4.2. Process design

Process design aims at developing rules, methodologies and software tools for selecting disassembly strategies and configuring manual or automated disassembly systems. Disassembly planning can help to find optimal strategies for complex products, with quantitative evaluation of dismantling costs and with an optimal management of all information about the product and its previous use (Fig.20).

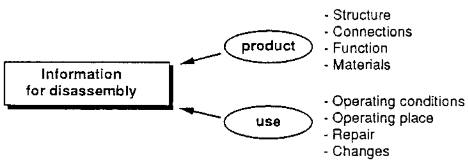

Fig.20: Information for disassembly [46]

In order to model the disassembly process, many companies and research laboratories are gaining experience of manual and automated disassembly of existing products. Some European automobile manufacturers (BMW, Ford, Volkswagen, FIAT, PSA) have set up dismantling centers where they analyze disassembly times in order to find the best methods for dismantling vehicles [26, 33, 36, 53, 107]. Similar initiatives have been taken in the electronic sector by IBM [31, 63] and Philips [116]. A guiding principle in disassembly is to remove the most valuable parts first and to stop disassembly when the marginal return on the operation becomes uneconomical; an optimal disassembly depth can be defined on that basis (Fig.21) [46, 106, 124].

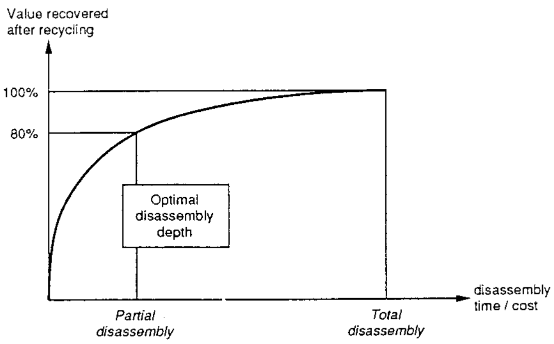

Fig.21: Optimization of disassembly depth [47]

A research group at IWB, Technical University of Munich, is working on disassembly of electric tools, with the aim of optimizing manual disassembly [37, 38, 81, 82, 83].
The focus at FAPS, Technical University of Erlangen-Nurnberg [46, 47, 62] and at Siemens [42, 114] is disassembly of electronic devices. In particular, disassembly of PCBs for sorting and separation of each different type is a challenging task. Results obtained include:
- understanding of problems arising when multiple disassembly directions and different fastening methods exist;
- analysis of information necessary for disassembly;
- analysis of different methods for PCB disassembly and definition of a proper operating sequence.

At IPU, TU Denmark, research is starting on flexible recycling centers for electronic devices. All aspects of the recycling process are taken into account from a life cycle design viewpoint, including environmental policy and resource recovery [18].
At IFH, Technical University of Braunschweig, automated dismantling of computers is being studied [60]. To disassemble external cover and motherboard, several techniques are under development, including optical recognition and unwelding of toxic components, grinding of the remaining components, separation through sieve, air and water stream, partially destructive removal of the cover.
Disassembly for recycling of printed circuit boards is also being investigated at the Technical University of Dresden [92].

A further step is the development of tools allowing sequence planning of manual disassembly and choice of automation level. Disassembly planning follows rules other than those for assembly planning. While assembly planners know the number of parts, their quality and material for the final, well-known product, disassembly planning has to deal with uncertainty in product configuration [103]. It is critical that the scope of the planning process is not reduced due to the unstructured product knowledge.
At IWF, Berlin, a standard disassembly methodology has been proposed, based on four phases (Fig.22) [59, 103]:
1) Product analysis, where valuable or reusable materials and parts are defined, which provides information for optimum disassembly depth.
2) Assembly analysis, where joining methods, component hierarchy and former assembly sequence are analyzed with regard to component separability and possible dismantling techniques.
3) Usage mode and effect analysis, which takes into account the imponderables of the dismantling process, generating possible deviations of a used product from its original state. The function of a component already gives hints on possible changes to its original states (use in humid environments is likely to produce corrosion).
4) Determination of dismantling strategy, which decides whether destructive, non-destructive or partly destructive disassembly should be chosen.

The result is a process plan, which provides information on disassembly steps, dismantling tools, fixtures, times, safety measures for workers and qualification needs [59].

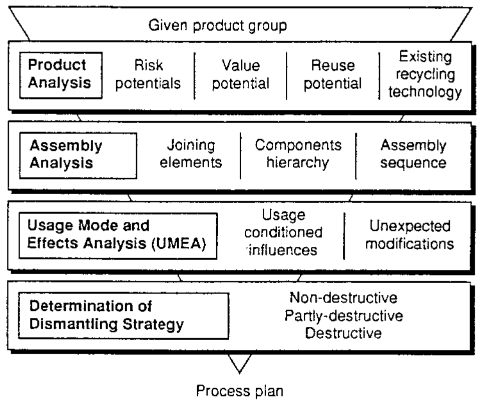

Fig.22: Disassembly process planning methodology [59]

Approach at IPA, Stuttgart, is based on a database containing recycling information on typical products (e.g. plotters, keyboards, system and storage units and monitors). Using the stored data (disassembly and disposal costs, recoverable values), economic analyses can be carried out. The method also consists in a specific set of questionaires for product analysis, which help to define the company specific recycling and disassembly profile of the products and to select products and components to be redesigned [99, 117].
Selection of disassembly strategies by economic balance of disassembly costs and recycling value is also being investigated at WZL, Aachen [45] and WBK, University of Karlsruhe [113].
Planning software may also be used to automatically program disassembly robots: Siemens is developing a Disassembly Process Control directly interfaced to a robot controller (Fig.23). It processes data coming from 3D sensors and collected by a shape recognition system. Disassembly sequences for macro-operations are stored in the robot control unit as program modules, which contains all the necessary process values. A man-machine interface interactively guides shape recognition, planning and downloading of program modules to the robot controller [39].

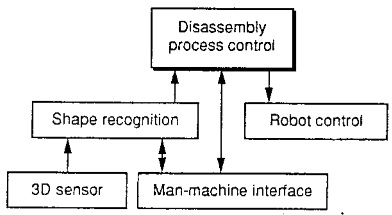

Fig.23: Control architecture of the Siemens disassembly robot cell [39]

4.3. System design

Research about system design aims at developing methodologies for:
- configuration of manual and automated disassembly facilities;
- economic justification of disassembly systems;
- organization of a logistic network for reclaiming, dismantling and recycling.

At IPA, Stuttgart, the concept of a flexible disassembly cell has been introduced. The cell consists of the following elements [99, 117]:
- one or more industrial robots, typically with six degrees of freedom;
- a cell control unit with a data base for robot subroutines and product features;
- flexible disassembly tools (screwdrivers, grippers, drills, laser cutting tools), to be handled by the robot using a standard interface;
- flexible disassembly fixtures;
- sensors (tactile, vision, laser) for process control and reaction to uncertainty in product configuration;
- input-output conveyors.

An industrial cell based on this concept has been applied to disassembly of telephones, with promising reliability and cycle times.
IWF, Berlin, is planning to set up a prototypical disassembly cell, comprising robots and flexible disassembly tools, integration of innovative disassembly techniques (water jet and laser cutting) and a control system capable of learning to perform standard operations automatically while allowing direct operator control

for new tasks [103]. Experiments in a disassembly and assembly cell have allowed components belonging to different series of transmissions to be automatically exchanged [101].
Non-destructive disassembly is a promising field for automation. In Japan, Tokyu Corporation has developed a flexible robot cell for disassembling valves of air brake equipment for railway carriers, currently running in a maintenance center [85].
Design of fixtures for manual and automated disassembly is a research topic at Siemens [39, 40]. A good fixture should be designed so as to simplify disassembly movements and avoiding damage to the individual parts, if they have to be reused. Fig.24 shows a disassembly fixture for PC keyboards.

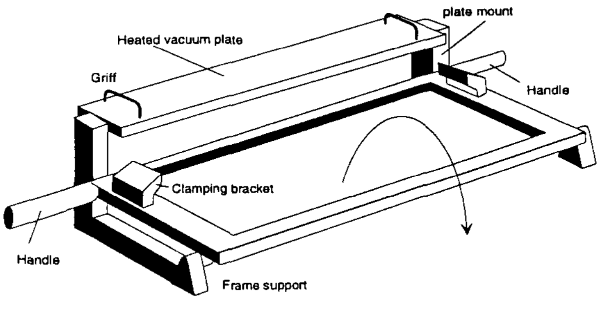

Fig.24: Disassembly fixture for PC keyboards [39]

Disassembly tools are application dependent and have to be frequently changed during the process. To avoid this disadvantage, at WBK, Karlsruhe it is planned to develop an integrated tool that combines the functionality required during all phases of the process. To cope with uncertainty in product configuration, selection and adaption of sensors is also studied [113].
Work on system design is also underway at WZL, Aachen [43], FAPS, Erlangen [46, 48], IWB, Munich [37, 38, 81, 82, 83], and at the German-French Institute for Automation and Robotics [19]. A common assumption is that disassembly system design has to be integrated with product and process design in a concurrent engineering environment. The key is to develop in parallel all design phases (requirements analysis, conceptual design, detailed design) for product, production system and disassembly system [37].
A topic being increasingly consolidated, mainly among European automobile manufacturers [9, 32, 35, 124], is the organization of a recycling infrastructure. Additional logistics of product collection is an important cost factor, which has to be reduced through an efficient network of decentralized disassembly factories, able to dismantle a variety of products [18, 59]. The structure commonly viewed as ideal consists of:

- a central technical and organizational facility, where time and motion studies are carried out in laboratories in order to develop disassembly methods suitable for industrial-scale processes;
- a network of dismantlers, which take back used products from customers, remove the recyclable parts and directly provide disposal of the residual waste; in the automotive sector, such a network already exist, and has to be coordinated by the manufacturer;
- a network of recycling facilities, which turn recovered material into new products, either in the original and in new sectors;
- a logistic structure, established by the manufacturer, which provides transportation of recovered material from dismantlers to recyclers.

Thus, the role of the manufacturers is restricted to technical and logistic support to dismantlers and recyclers. Manufacturers have not to deal with activities where they are not traditionally involved (Fig.25).

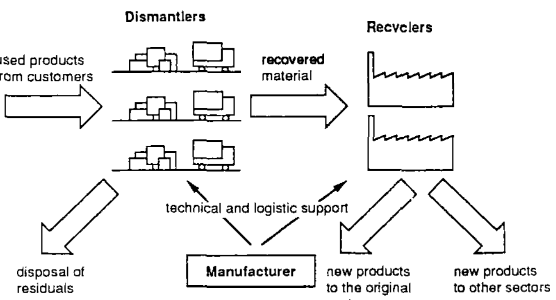

Fig.25: Organization of a dismantling structure

It is not easy to build a similar structure for electronic products, because of the logistic differences between residential users and large industrial and commercial users. The latter can provide a uniform end-of-life product stream, since they are bulk users and have close links with the original equipment suppliers (manufacturers or dealers). Residential customers are a much more dispersed source of products with little uniformity in the waste stream. In this case, collection of used equipment should be submitted to retailers or municipal authorities [42, 97].

5. Future opportunities

While the initial industrial experiences are widening the knowledge of the different facets of the disassembly problem, an increasing attention to research on product, process and system design can be expected. Future developments will depend on legislation, that is going to set up the constraints for recycling. To meet the requirements of the expected regulations, enterprises should start to take responsibility for recycling their products themselves or making them available for the recycling process [59].
Development of innovative disassembly factories is likely to involve interdisciplinary research groups from the areas of production technology, logistics, design, architecture and marketing [103]. Cooperative research currently follows three main channels [97]:

- product based efforts, carried out by manufacturers;
- material based efforts, among polymer producers and plastics processors;
- vertical collaboration, between suppliers and manufacturers.

Disassembly research should also be promoted through international cooperation. European strategic programmes (EUREKA, BRITE, ESPRIT) can represent good sources of activation [64, 76]. Some of the current funding channels are [97]:

- EUREKA EUROENVIRONMENT umbrella project, concerning several sectors of environmental management, including handling and disposal of industrial waste;
- EC Environment Programme Group II.2 (formerly REWARD), focused on the global problem of waste management and recycling;
- EC Raw Materials and Recycling Programme, in the area of material reprocessing technology.

Future research efforts will be directed to make disassembly of new products economically justified. A number of strategic topics need to be faced, concerning recycling, life cycle design and disassembly technology [3, 17].

Recycling

To allow more effective material recycling, new processes need to be found and existing processes need to be enhanced. The critical problems to be solved are:

- recycling of rare metals, plastics and composites;
- material recognition and sorting;
- material compatibility criteria.

Life cycle design

Each decision about product recycling has to take life cycle design into consideration. Work is needed to develop information technology as a support to sustainable industrial production: the major areas are:

- product life cycle assessment tools based on databases and CAD integration;
- decision support systems for logistic support.

Disassembly technology

The priority in this field is the development of tools, equipment and machinery for automated disassembly of today's products. This will pave the way to effective design for recycling of future products.

6. Conclusions

The paper has reviewed the current research activities on disassembly for recycling of industrial and consumer products. The importance of the problem is recognized by most of the industrially developed countries, with different emphasis on the issues concerning legislation, standardization, basic research and industrial implementation. Nevertheless, it is easy to foresee that only a development of disassembly technology (now still in its infancy) can give a decisive impulse to the development of easy-to-recycle products and to computer-based design of disassembly processes and systems.
Future activities will involve many different competences, in which production technology plays a central role. The interdisciplinary nature of the problem, its strong implications in every life cycle phase of products, and the unquestionable technological interest, call for an ever increasing involvement of CIRP in this field.

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References

[1] "Coding and recycling thermoplastics parts", *IBM, CS 5-0001-006*, 1992
[2] "Design for recycling", *GE Plastics*, 1991
[3] "Ecofactory: concepts and R&D themes", *New Technology Japan*, 1992
[4] "Environmentally conscious design practices", *IBM Semea*, 1992
[5] "Ethos", *GE Plastics*, 1992
[6] "Frigorifero monomaterico Green Frost", *Tech. Rep., EniChem Polimeri*, 1992
[7] "Kunststoffkomponenten: am Anfang an das Ende denken", *Plastverarbeiter*, 41-7, 1990, pp. 106-110
[8] "Leading-edge engineers design for recycling", *Machine Design*, Jun 24, 1991, pp. 12-14
[9] "Recyclage automobile: de gros effort", *Plastiques modernes et elastomeres*, Jul/Aug, 1991, pp. 58-60
[10] "Recycling and the automobile", *Automotive Engineering*, Oct, 1992, pp. 41-57
[11] "Recyclinggerechtes Konstruieren mit Thermoplasten, besonders fur Elektro- und Elektronikgerate sowie Datentechnikgehause", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[12] "VDI Richtlinie 2243: Konstruieren recyclinggerechter technischer Produkte", *VDI-Verlag*, 1991
[13] A. Addeo, "Il contributo delle tecnologie delle materie plastiche alla semplificazione dei problemi ecologici", *Tech. Rep., CSI-Montedison*, 1992
[14] L. Alting, "Designing for a lifetime", *Manufacturing Breakthrough*, May/June, 1993, pp. 29-33
[15] L. Alting, "Life cycle design", *Concurrent Engineering*, 1-6, 1991, pp. 19-27
[16] L. Alting, "New dimensions in manufacturing", *Tech. Rep., Inst. of Manufacturing Engineering, TU Denmark*, 1992
[17] L. Alting, J. Jorgensen, "The life cycle concept as a basis for sustainable industrial production", *Annals of the CIRP*, 42-1, 1993
[18] L. Alting, J.B. Legarth, "Flexible production systems for disposal of complex industrial products", *Proc. Seminar on Life Cycle Engineering*, 1993
[19] D. Barth, A. Gerhardt, H. Schmied, "Integration der Demontage in das produktionstechnische System", *ZwF*, 88-4, 1993, pp. 141-145
[20] W. Beitz, U. Kurella, M. Schmidt-Kretschmer, "Grundlagen der montage- und demontagegerechten Konstruktion", *VDI Berichte 999*, 1992, pp. 131-156
[21] W. Bernhart, "Bewertung von Montier- und Demontierbarkeit in der Entwurfsphase als Element eines Lifecycle-Design", *VDI Berichte 999*, 1992, pp. 297-316
[22] H. Bley, S. Dietz, A. Muller, "Wirtschaftliche Montage durch eine montagegerechte Konstruktion und rechnerunterstutze Montageplanung", *VDI Berichte 999*, 1992, pp. 257-275
[23] A. Bonvini, V. Cocca, F. Mascia, A. Verzelli, "Asciugabiancheria a condensazione d'aria (Drier Condensa)", *Tech. Rep., CSI-Montedison*, 1991
[24] G. Boothroyd, L. Alting, "Design for assembly and disassembly", *Keynote Paper, Annals of the CIRP*, 41-2, 1992, pp. 625-636
[25] L. Brooke, "Plastics recyclability update", *Automotive industries*, Apr, 1991, pp. 40-44

[26] L. Brooke, G. Kobe, J. McElroy, C.A. Sawyer, "Recycling: what's the problem?", *Automotive Industries*, Sep, 1992, pp. 44-53
[27] J.P. Brun, "La valorisation des pneumatiques usage'", *Ingenieurs de l'Automobile*, 678, 1993, pp. 56-57
[28] G. Carrubba, "Ecobalance: una opportunita' per migliorare la scelta dei materiali nel campo della progettazione automobilistica", *Tech. Rep., Dow Chemical*, 1992
[29] G. Clerici, "Il riciclo dei materiali per accumulatori", *Tech. Rep., CGA-Magneti Marelli*, 1992
[30] J.A. Collins, "Plastics and the environment: solving the problem of use and abuse", *Environmental Engineering*, Jun, 1992, pp. 25-31
[31] S.D. Consonni, "Il riciclo delle apparecchiature elettroniche IBM", *IBM Semea*, 1992
[32] M. de Kilmaine, "Filieres de recuperation", *Ingenieurs de l'Automobile*, 678, 1993, pp. 38-41
[33] J.M. Del Vecchio, "Le nouveau concept de recyclage automobile", *Ingenieurs de l'Automobile*, 678, 1993, pp. 50-52
[34] P. Dewhurst, "Design for disassembly", *Rep. #63, Dept. of Industrial and Manufacturing Engineering, University of Rhode Island, Kingston, RI*, 1992
[35] S. Di Carlo, "Car recycling: the FIAT approach", *Recycle '93 Int. Forum and Exposition*, 1993
[36] S. Di Carlo, "La proposta FIAT Auto per il riciclaggio delle vetture dismesse", *Tech. Rep., FIAT Auto*, 1992
[37] A. Dieterle, "Disassembly of electric tools", *Proc. Seminar on Life Cycle Engineering*, 1993
[38] A. Dieterle, "Montage und Demontage in einem gemeinasamen Ansatz", *Tech. Rep., IWB, Munich, Germany*, 1992
[39] H. Ebach, "The influence of consideration on the life cycle on design", *Proc. Seminar on Life Cycle Engineering*, 1993
[40] H. Ebach, C. Scherer, H. Streibelt, "Einfluss der Lifecycle-Betrachtung auf die recyclinggerechte Produktgestaltung", *VDI Berichte 999*, 1992, pp. 49-69
[41] S. Eder, G. Werner, "Elastomere im Automobil: Umweltbewusste Fahrzeugentwicklung und -entsorgung", *Kautschuk, Gummi, Kunststoffe*, 44-6, 1991, pp. 572-580
[42] J.K. Ertel, "Decree on electronic scrap: impacts on the industry", *Tech. Rep., Siemens AG, Munich, Germany*, 1993
[43] W. Eversheim, M. Linhoff, "Zukunftsperspektive Demontage", *VDI-Z*, 134-6, 1992, pp. 83-86
[44] W. Eversheim, M. Hartmann, "Monetare Bewertung von montagegerechten Produkten", *Tech. Rep., WZL, Aachen, Germany*, 1992
[45] W. Eversheim, M. Hartmann, B. Katzy, "Zukunftspotential Produktgestaltung", *VDI Berichte 999*, 1992, pp. 1-25
[46] K. Feldmann, "Recycling of electronic devices", *Proc. Seminar on Life Cycle Engineering*, 1993
[47] K. Feldmann, R. Hopperdietzel, "Recycling of electronical scrap material, *Tech. Rep., FAPS, Erlangen, Germany*, 1992
[48] K. Feldmann, R. Hopperdietzel, "Wirtschaftliches Recycling durch automatisierte Demontage", *ZwF*, 88-4, 1993, pp. 148-150
[49] F.R. Field, J.P. Clark, "Recycling of USA automobile materials: a conundrum for advanced materials", *ATA*, 44-8/9, 1991, pp. 541-555
[50] T. Folster, "Life-Cycle Analysis: the development of a new tool for ecological evaluation", *Proc. Seminar on Life Cycle Engineering*, 1993
[51] F. Forcucci, "La filosofia Himont per la segmentazione dei materiali e l'impiego dei materiali omogenei: tecnologie per il riciclo", *Tech. Rep., CSI-Montedison*, 1992
[52] F. Forcucci, D. Tompkins, "Automotive interiors: design for recyclability", *Proc. SAE Int. Conference and Exposition*, 1991, pp. 41-46
[53] H. Franze, "Konstruieren furs Recyceln", *Automobil-Produktion*, Sep 1992, pp. 88-90
[54] C.R. Fussler, B. Krummenacher, "Ecobalances: a key to better environmental material choices in automobile design", *Materials and Design*, 12-3, 1991, pp. 123-127
[55] J. Gardner, "IBM labeling computer parts for disassembly", *Plastics News*, Jun 1, 1992, p. 4
[56] M. Grahler, "Mechanische Zerlegungsverfahren zur Ruckgewinnung von metallischen Werkstoffen aus dem Elektronikschrott", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[57] A. Hampp, "Produktrecycling: das Siemens-Nixdorf-Konzept", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[58] M. Hartmann, F. Lehmann, "Demontage", *VDI-Z*, 135-1/2, 1993, pp. 100-110, and 135-3, 1993, pp. 92-102
[59] C. Hentschel, "The greening of products and production: a new challenge for engineers", to be presented at *Int. Conf. on Advances in Production Management Systems*, 1993
[60] J. Hesselbach, H.K. von Werder "Elektronikschrottrecycling: der momentane Technikstand erfordert Aktivitaten", *Tech. Rep., IFH, TU Braunschweig*, 1993
[61] D.J. Holt, "SAE J1344", *Automotive Engineering*, Nov, 1991, p. 4
[62] R. Hopperdietzel, J. Franke, G. Liedl, J. Schiebisch, D. Tartler, M. Fischer, P. Schuderer, "Recycling elektronischer Gerate", *Elektronik*, 15, 1992, pp. 30-36
[63] F. Jahnig, "Recycling vov elektronischen Altgeraten", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[64] F. Jovane, "Results of the EUREKA FAMOS research programme: a European contribution to manufacturing technoogy", *Robotics and Computer-Integrated Manufacturing*, 10-1/2, 1993, pp. 13-19
[65] F. Jovane, L. Carlesi, "Sull'ingegneria della qualita'", *CNR*, 1993
[66] J. Jorgensen, M. Hauschild, "The EDIP project: development of sustainable industrial production, *Proc. Seminar on Life Cycle Engineering*, 1993
[67] R. Junemann, P. Muller, "Das Lebenszyklus-Konzept", *VDI Berichte 999*, 1992, pp. 391-409
[68] J. Kagan, "PS/2: ECP consideration", *IBM*, 1992
[69] M. Kahmeyer, T. Leicht, "Dismantling Facilitated", *Kunststoffe German Plastics*, 81-12, 1991, pp. 30-32
[70] D. Keller, "Erfolgsfaktoren eines proaktiven Umweltmanagements und -marketings", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[71] M. Kennedy, "Plastics auto group drives auto industry toward recycling", *Machine Design*, May 7, 1992, pp. 14-15
[72] H. Kohler, A. Eberle, "Aktuelle Werkstoffstrategien in der Automobilindustrie unter besonderer Berucksichtigung des Recyclinggedankens", *Giesserei*, 80-2, 1993, pp. 37-41
[73] F.L. Krause, F. Golm, "Consideration of environmental aspects in the design process", *Proc. Seminar on Life Cycle Engineering*, 1993
[74] K.R. Kreisher, "Recyclability keys PP growth in European autos", *Modern Plastics International*, Oct, 1991, pp. 50-52
[75] R. Kugler, J. Arnolds, A. Kempte, "Konzeption und Realisierung produktorientierter Anforderungen am Beispiel einer Waschmaschine", *VDI Berichte 999*, 1992, pp. 27-48
[76] M. Lanfranchini, "Les filieres et procedes de recuperation", *Ingenieurs de l'Automobile*, 678, 1993, pp. 48-49
[77] L. Leonard, "Designing for the environment", *Plastics Design Forum*, May/June, 1991, pp. 25-32
[78] V. Mangold, "Simpler solutions to robotisation", *The Industrial Robot*, Mar 1989, pp. 33-34
[79] A. Mantegazza, "I pneumatici usati", *Tech. Rep., Pirelli*, 1992
[80] J. Milberg, Pictures about IWB activity on disassembly, *IWB, Munich, Germany*, 1992
[81] J. Milberg, A. Dieterle, "Demontage von Elektrokleingeraten", *Tech. Rep., IWB, Munich, Germany*, 1992
[82] J. Milberg, A. Dieterle, "Integration der Demontage in die Produktgestaltung", *Tech. Rep., IWB, Munich, Germany*, 1992
[83] J. Milberg, G. Schuster, J. Fischbacher, A. Dieterle, "Montage- und demontagegerechte Produkte durch Integration von Produkt- und Arbeitssystemgestaltung", *Tech. Rep., IWB, Munich, Germany*, 1992
[84] B. Miller, "SPI launches car-recycling program", *Plastics World*, Apr, 1992, p. 16
[85] M. Miyata, "Development of a robot of a robot system for automatic disassembly and assembling of brake equipment parts", *Japanese Railway Engineering*, 119, 1992, pp. 14-18
[86] R. Murchie, "Design for recycling", *Plastics and Rubber Int.*, Jun/Jul, 1992, p. 7
[87] J. Nutting, "New materials, resources and the environment", *Metals and Materials*, Feb, 1990, pp. 83-86
[88] C.J. Olsen, "Design for maintenance", *Industrial Management*, Mar/Apr, 1992, p.1
[89] D.L. Reinhard, "Can Glass Fiber Reinforced Polypropylene composites be recycled?", *SAE Tech. Paper #920855*, 1992
[90] N.C. Remich, "Design for recycling", *Appliance Manufacturer*, Nov, 1992, pp. 32-35
[91] A. Rogez, "Renovation ou valorisation des machines tournantes", *Ingenieurs de l'Automobile*, 678, 1993, pp. 60-63
[92] G. Rohrs, "Konstruktions und Demontageprinzipien fur das Recycling von Leiterplatten", *Tech. Rep., Inst. fur Electronik-Technologie, TU Dresden, Germany*, 1992
[93] E.P. Rose, S. Evans, "A robust Design For Recyclability methodology", *Proc. CIM-Europe Annual Conference*, 1993, pp. 201-211
[94] J. Rosenthal, "Recycling: development and technology update", *Glass Machinery, Plants and Accessories*, 4-1, 1991, pp. 47-51
[95] L. Rosti Rossini, "Riflessi della sfida ambientale sulla progettazione carrozzeria", *Tech. Rep., FIAT Auto*, 1992
[96] N. Roth, "Disassembly and recycling of electrotechnical and electronic products", *Tech. Rep., Siemens AG, Munich, Germany*, 1992
[97] R. Roy, "End-of-life electronic equipment waste", *Tech. Rep.*, CEST, 1991
[98] T. Rummler, "Requirements for used cars recycling in the Federal Republic of Germany", *Ingenieurs de l'Automobile*, 678, 1993, pp. 44-46
[99] T. Schmaus, M. Kahmeyer, "Design for disassembly: challenge of the future", *Proc. Int. Forum on Design for Manufacture and Assembly*, 1992
[100] H.J. Schwarz, "Umweltfreundliche Verwertung von Bildschirmen, Tastaturen, Druckern und Steuereinheiten durch ICL", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[101] G. Seliger, H.J. Heinemeier, S. Neu, "Robotergefuhrte Demontage und Montage von Kleingetrieben fur die Austauschfertigung", *ZwF*, 88-6, 1993, pp. 245-248
[102] G. Seliger, C. Hentschel, A. Kriwet, "Design for disassembly in the framework of Life-Cycle Design", *Proc. Seminar on Life Cycle Engineering*, 1993
[103] G. Seliger, C. Hentschel, A. Kriwet, "Disassembly of complex electronic products for further recycling", *Tech. Rep., IWF, Berlin, Germany*, 1992
[104] G. Seliger, E. Zussman, A. Kriwet, "Integration of recycling consideration into product design: a system approach:, *Proc. NATO ARW*, 1993
[105] G. Seliger, E. Zussman, A. Kriwet, "Recycling consideration in the system life-cycle", *Proc. Seminar on Life Cycle Engineering*, 1993
[106] M. Simon, "Design for dismantling", *Professional Engineering*, Nov, 1991, pp. 20-22
[107] B. Siuru, "From scrap heap to showroom", *Mechanical Engineering*, Nov, 1990, pp. 66-68
[108] E. Sprow, "The mechanics of remanufacturing", *Manufacturing Engineering*, 3, 1992, pp. 38-45
[109] D. Stover, "Designed for disassembly", *Popular Science*, Jan, 1991, p. 22
[110] V.A. Tipnis, "Activity and economic modeling for design for sustainability", *Proc. Seminar on Life Cycle Engineering*, 1993
[111] V.J. Tipnis, "Evolving issues in product life cycle design", *Annals of the CIRP*, 42-1, 1993, pp. 169-173
[112] V.A. Tipnis, "Product life-cycle economic models - towards a comprehensive framework for evaluation of environmental impact and competitive advantage", *Annals of the CIRP*, 40-1, 1991, pp. 463-466
[113] C. Tritsch, "Strategies for disassembly and life-cycle design of products", *Tech. Rep., WBK, Karlsruhe, Germany*, 1993
[114] G. Ullmann, "Auswirkungen der Elektronikschrott-Verordnung auf Kostenrechnung und Finanzierung im Unternehmen", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[115] B. Vernyi, R. Shinn, "Pyrolysis, dismantling become target of auto recycling efforts", *Plastics News*, Mar 11, 1991, pp. 1-22
[116] U. von Essen, "Probleme mit dem Elektronikschrott", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[117] H.J. Warnecke, M. Schweizer, M. Kahmeyer, "Flexible disassembly with industrial robots", *Proc. 23rd Int. Symp. on Industrial Robots*, 1992, pp. 547-554
[118] A. Weber, "Aspects of plastic waste from abandoned vehicles", *Proc. Conf.: Plastics Recycling, Meeting the Challenge*, 1991, pp. 20/1-37
[119] A. Weber, "Plastics in automotive engineering: use and re-use", *Materials and Design*, 12-4, 1991, pp. 199-208
[120] T.R. Welter, "Design for disassembly: it's the new environmental consideration for products", *Industry Week*, Jun 17, 1991, pp. 44-45
[121] A. Wende, G. Grieger, "Hinweise zur entsorgungsfreundlichen Konstruktion von Geraten", *Produktrecycling in der Elektro- und Elektronikindustrie*, 1992
[122] H. Weule, "Life cycle analysis: a strategic element for future products and manufacturing technologies", *Annals of the CIRP*, 42-1, 1993, pp. 181-184
[123] K.W. Witte, S. Stolze, "Neue Organisationformen fur die montage- und recyclinggerechte Konstruktion", *VDI Berichte 999*, 1992, pp. 341-374
[124] G. Wittenberg, "Life after death for consumer products", *Assembly Automation*, 12-2, 1992, pp. 21-25
[125] P. Zeranski, "Neue Chancen durch Altauto-Verwertung", *ATZ*, 94-10, 1992, pp. 532-533
[126] R. Zust, "4-Phase model for environmentally-compatible product creation", *Proc. Seminar on Life Cycle Engineering*, 1993
[127] R. Zust, R. Wagner, "Approach to the identification and quantification of environmental effects during product life", *Annals of the CIRP*, 41-1, 1992, pp. 473-476

applied to simplify disconnecting operations in either case.
Accessible drainage points - When an assembly contains liquids, they can be an obstacle to disassembly. Openings for draining these substances should be provided in easily accessible locations.
Choice of fasteners - Fasteners have to be selected so that they could be easily removed or destroyed. For metal parts, threaded fasteners are the most favourable option, since most of the other choices require high disassembly forces. For plastic parts, more alternatives have to be carefully evaluated [2, 77]:

- adhesives create some problems, because disassembly forces are high and adhesive residue must be removed before the parts can be recycled; if a label has to be stuck on the part, a solution is to make the primary part, the label and the adhesive of the same material (polycarbonate, for example, can be used for all tasks) [90];
- ultrasonic, spin, vibration, hot-plate and hot-gas welding involve in most cases compatible materials, therefore separation may not be required at all;
- heat staking is easily removable, as only a small amount of material provides the fastening force (typically the tip of a protrusion);
- induction welding requires destructive disassembly, and the removal of the metal left inside the part (a contaminant for recycling);
- threaded fasteners can be simply unscrewed; to save time, screws can be pulled out of their bosses, but if they remain attached to a part, reprocessing equipment could be damaged;
- snapfit is the ideal joining method; it requires no additional parts to be separated, no additional materials that can be possible contaminants, and can be disconnected quickly and efficiently (Fig.15 [2]).

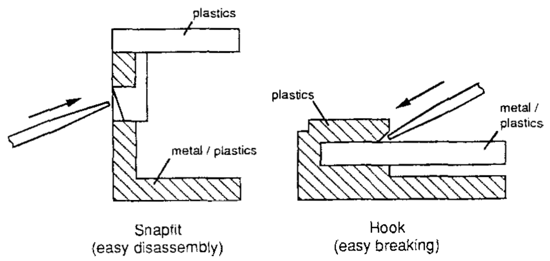

Fig.15: Easily removable fastening methods [2]

Minimum number of fasteners - Fewer fasteners to keep two components together simply means fewer disassembly operations.
Multiple fastening - If few fasteners keep a stack of many components together, the overall disassembly time is reduced.
Easily accessible separation points - Interconnection points and joints have to be easily accessible for separating parts by hand or automatically, possibly at predetermined break areas [2].
Simple disassembly movements - For ease of automation, disassembly should consist in simple translations along one or few directions. Need for complex movements (e.g. rotation) for disassembly should be avoided [104]. This often requires a redesign of products into easily accessible modules, with a stacked construction [2].
Centering on base - Automated disassembly is facilitated if unstable configurations are avoided. If, after removing a series of fasteners, the next component to be removed is centered on another one, it can be ready to be grasped by the robot.
No inserts - Metal insert in a plastic part have to be removed before recycling the part, often with difficult access [77].

Easy handling
The following criteria contribute to allow safe handling by workers or automated manipulators.
Grasp provision - Assembled parts must have surfaces available for robot grasping [69]. As an example, Fig.16 shows two alternative solutions for the removal of rubber feet from a keyboard [96].*Rigid parts* - Parts with bending behaviour are difficult to manipulate, and should be avoided whenever possible [69].
Toxic part insulation - Poisonous substances should be enclosed in sealed units to avoid injuries to disassembly operators [69].

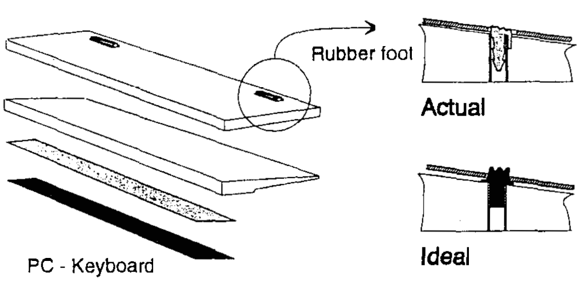

Fig.16: Design for disassembly on a PC keyboard [96]

Easy separation
The following criteria contribute to ease separation and shredding, two phases which should follow disassembly.
No secondary finishing - Secondary operations usually involve additional material to be removed, unless its nature or concentration do not raise recycling problems. Critical processes are painting (which can affect recycling of plastics), filling of blow molded parts with insulating foams (virtually impossible to remove), plating (difficult to remove on a large scale until a method of reversing the process is found) [2, 77].
Sorting features - To avoid mixing different materials, identification should be accepted as a common practice. The main alternatives are [2, 55, 77]:

- in-mold coding, which also allows adding specific material descriptions; codes should be engraved in the mold and reproduced on a non-appearance surface of the product;
- bar coding, which can allow automated sorting; the information is added to the parts by in-molding or laser-marking;
- color coding, which consists of having, within one assembly, all parts made from the same material in an identical color.

However, it is argued that the proposed codes are not a definite solution, since in destructive disassembly many parts can be recovered incomplete. The use of a chemical tracer through the part has been proposed as an alternative [86]. Moreover, material coding is not practicable for automated separation, as experienced by Ford [124], mainly because original labels or colors may be altered by usage. A satisfactory solution still has to be found for this problem.
Shredding suitability - Non shreddable materials (e.g. concrete counterweights for washing machines) should be avoided [104].

Variability reduction
Automated disassembly strongly requires reducing manipulation costs by reducing part variability. The following rules should be followed:
Part standardization - The same parts or subassemblies should be used for different varieties of a product.
Fastener standardization - The number of fastener types should be minimized, in order to simplify tooling requirements.

Benefits of introducing design for disassembly criteria in designing new products will not be realized before significant amounts of used products are returned at the end of their life cycle. This will take medium-long time, depending on expected average lifetime (Fig.17).

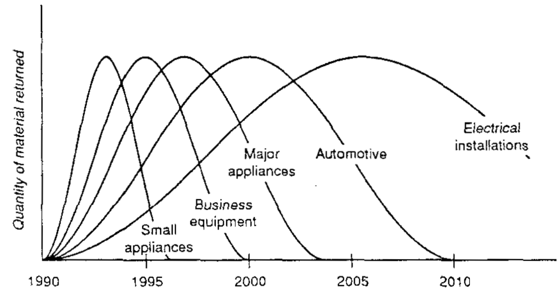

Fig.17: Distribution of end-of-life product return [2]

Industry is beginning to design products for ease of disassembly and recycling. Some examples can be mentioned:

- car subassemblies (instrument and door panels, console, bumpers) made with a single thermoplastic material (Himont [52]);
- small kitchen appliances entirely made of compatible plastics (Polymer Solutions [8, 77, 109, 120]);
- personal computers where all plastic parts are made of recyclable blends (IBM [68], ICL Data [100]);
- car prototypes with large use of recyclable engineering polymers (Pininfarina [5]);
- monomaterial refrigerators and washing machines (EniChem Polimeri [6], Zanussi [106]);
- easy-to-recycle copy cartriges with fasteners replacing ultrasonic welding (Xerox [90]);

Some research groups are working at methodologies and software tools to support product designers in the conceptual design stage.
At CIM Institute, Cranfield, research focuses on disassembly oriented life cycle analyses where recyclability of products is evaluated under possible future trends in recycling technology and economy (new recycling techniques, landfill cost growth) [93].
At ETH, Zurich, an evaluation procedure has been proposed in order to support product design according to conflicting design for disassembly criteria. Each criterion is given a weight and final decision is taken on the basis of a scaling of all relevant criteria [126].
Some early results are also available on evaluation methodologies useful in the detailed design stage.
At WZL, Aachen, a Disassembly Evaluation Procedure has been proposed. It is based on an index of ease of disconnecting and handling, which is calculated in a table-driven way for each single part or subassembly to be removed, and is then evaluated for the whole assembly as an average value (Fig.18) [43, 44].

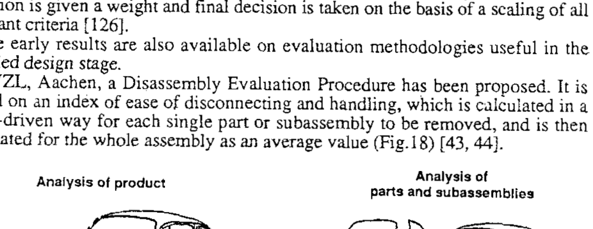

Fig.18: Disassembly evaluation procedure [43]

A dismantling suitability evaluation has been proposed at Siemens, mainly based on the number of parts and disassembly directions (Fig.19 [96]).