Life Cycle Engineering and Design

Leo Alting (1), Jens Brøbech Legarth

Abstract

This paper addresses the state-of-the-art in life cycle engineering/design. Actions taken by industry are discussed followed by a focus on life cycle design strategies, with special emphasis on design for low energy consumption in the use phase and design for disassembly. Life cycle design tools and methods and tools for design for recycling are further discussed generally with an overview of the tools most used by life cycle engineers. Finally, the implementation of life cycle design systems in industry's product development schemes is discussed.

Key Words: Environment, product design, disassembling.

Acknowledgements

The authors would like to acknowledge all who have contributed to this paper with suggestions and documentation of their work. Special thanks to Prof. R. Züst and group, Ing. G.-L. Baldo, Prof. K. Iwata, Prof. S. Takata, Dir. C. Hebert, Prof. K. Feldmann, Dipl.-Ing. H. Scheller, Prof. G. Seliger and group, Prof. F.-L. Krause, Dr. H.O. Haller, Dr. M. Ludwig, Dr. Haepp, Dr. Bessey, Prof. H.-J. Bullinger and group, Prof. H. Weule and group, Dr. A.L.N. Stevels, Dr. B. van der Ven, Dr. J. Kortman, Dr. A. Elsen, Prof. H.J.J. Kals, Dr. R. Heijungs, Prof. L. Cser, Prof. V.A. Tipnis, Dr. T.E. Graedel, Dr. B. Nordman, Mrs. R. Nedermark, Dir. J. Overgaard, Mr. H. Bundgaard, Vice Pre. J. Strömblad, Mr. L. Karlson, Prof. L.-G. Lindfors, Dr. T. Ekvall, and the staff of the Life Cycle Center, Copenhagen for their many fruitful inputs.

1. Introduction

The issues of environmental preservation have attracted increased worldwide attention throughout the latter part of this century, reaching new heights at the UNCED conference in Rio de Janeiro in 1992. Seemingly pre-set factors like the ever growing world population and the increasing demand for wealth by the less developed countries are threatening to exhaust our so-called environmental space (1) - the reserves of natural resources and the amount of pollution the earth can cope with. To be able to still fit into the available environmental space also in the future, the concept of sustainable development first introduced in the Brundtland report (2), is now gaining momentum in many areas of human activity. Not least in the manufacturing industry, where the truly great contemporary challenge lies in supplying the world community with material wealth, utilizing a limited amount of environmental space. Contributing to a sustainable society is becoming a survival issue in corporate development (3).

When it comes to the role of the manufacturing industry in ensuring a sustainable development, the message is simple: It has to greatly reduce the use of raw materials and the impact on the external environment, while preserving or improving the functionality of the products. The message is simple, but the way to get there is less simple. Agenda 21 suggests that the manufacturing industry implements environmental management systems and focuses on product stewardship (4). After two decades of end-of-pipe solutions to environmental problems dealing with the manufacture of the products rather than the products themselves, we now see a definite focus on the product as the contributor to resource and environmental problems on the one hand, and as the target of innovation on the other (5,6).

Manufacturers are becoming responsible for the environmental performance of their products throughout the products life cycle, from extracting the raw materials to the disposal of the products at their end-of-life. To incorporate environmental issues and parameters across the life cycle of a product into product development is the discipline of life cycle engineering/design, and this paper gives the state-of-the-art in modern environmental design strategies (section 2) along with overview of tools and methods (section 3) and a discussion of the implementation of these new methods in industry (section 4). Focus is on the developments in both industry and the academic world, as well as on international initiatives (7).

2. Concepts and strategies

2.1 Action taken by companies towards life cycle engineering in manufacturing

Business will play a vital role in the future health of this planet. As business leaders, we are committed to sustainable development... A quote from the Declaration of the Business Council for Sustainable Development (BCSD) (8), created in conjunction with the UNCED conference in Rio in 1992 and featuring some 50 chief executives from major corporations in industrialized nations worldwide. This quote clearly reflects not only that the business community does have a role to play, along with governments and NGOs, in moving towards a sustainable global development, but also that the business community is ready to meet this new challenge.

One result of the Rio conference was a set of actions that the business community need to take in contributing to the progress towards a sustainable global community (4). Actions needed go beyond compliance with environmental regulations to include the implementation of environmental management systems and product stewardship schemes, human resource development and the transfer of modern technology to developing countries. It is further important that the business community takes active part in the ongoing international work on environmental standards and procedures, and that businesses offer transparency concerning the environmental consequences of their activities, thus, satisfying also non-commercial stakeholders.

Viewing the member list of the BCSD indicates that the front-runners taking action are the large successful international corporations. And the actions they take pretty much correspond to those actions indicated by the Rio conference to be necessary. When dealing with the work needed inside a company, focus issues are environmental management systems (EMS) and product stewardship schemes, as well as the education and training of staff functions and the work force in how to handle corporate environmental issues. EMS standard initiatives are currently the British BS 7750 standard (9), published in 1992 and reviewed in 1994, the coming EMAS standard of the European Community (10), which will recognize national EMS standards meeting its minimum requirements and the result of the ISO technical committee TC 207's work, the ISO 14001 standard (11) expected to be published in 1996. Environmental management systems generally require that the company has full knowledge of the environmental consequences of its actions, concerning both manufacturing sites and products, that this knowledge is regularly updated and offered to the public and that concern for the environment is an active part of the everyday working situation of chief executives and blue collar workers alike.

The 1995 and 1996 action plan for Asea Brown Boveri's (ABB) environmental management program is shown in figure 1 as an example of the immediate action taken by a large pro-active company (12). The plan is based on the presumption that the ISO 14001 environmental management standard will be published in the 1st half of 1996. In implementing EMS ABB applies a three phase program. In phase one, 430 manufacturing sites in 35 countries were selected from a total of 520 sites in 46 countries as those with the greatest improvement potentials. During 1993 and 1994 a Country Environmental Controller was appointed in each of the 35 countries, and a Local Environmental Control Officer was appointed for each manufacturing site. This task force has as its first job to inventory current impacts on the environment from ABBs activities and to identify preliminary steps needed to improve performance. In phase two, underway since 1994, certain manufacturing sites, business units and large projects were chosen to implement pilot EMS projects. The second phase involves the extension of focus to include ABB products as well in pilot life cycle assessment studies also up-stream from the manufacturing phase including the evaluation of the environmental performance of suppliers. In phase three, starting in 1996, pilot experience is extended to all manufacturing sites, business units and large projects.

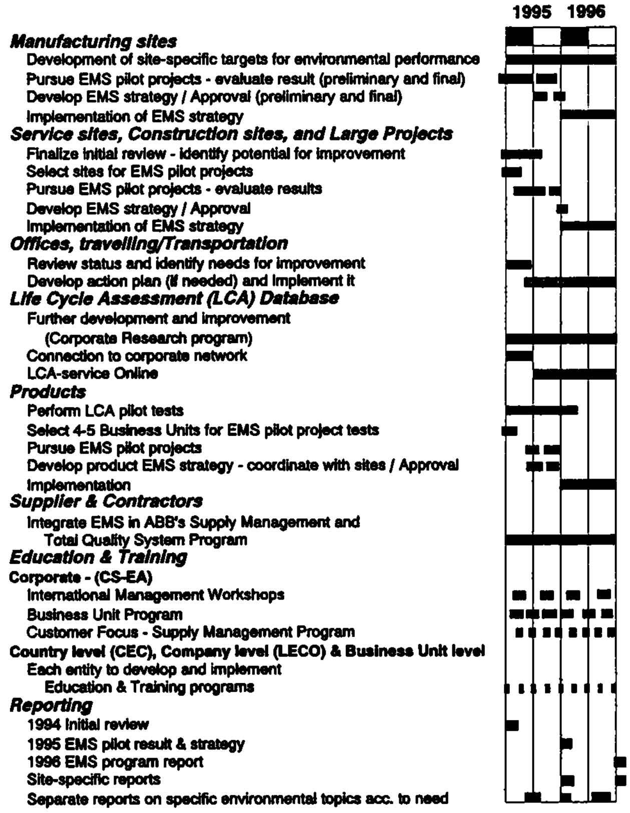

Figure 1 ABB Environmental Management Program. Action plan 1995 and 1996 (12)

2.2 Life cycle engineering/product stewardship

Product stewardship is an intrinsic part of any EMS action plan, in that the responsibility of the company goes beyond its operations to include the responsibility for their products' environmental performance throughout the product life cycle: pre-manufacture, manufacture, use, disposal and transportation (5).

Product stewardship as a means of pollution prevention involves a whole range of issues related to the environmental performance of products in all life cycle phases. It means to choose construction materials with small environmental rucksacks, to look into the operations of suppliers, to take a close look at the environmental performance of manufacturing processes, and to choose accordingly, to be aware of the environmental burdens of all means of transportation, to design products for optimum environmental performance in use, including serviceability, and to plan the products end-of-life fate. All these parameters are largely laid out in the development and design of the product, and to take these issues into account in product development is the scope of *life cycle engineering* (6).

Life cycle engineering is the art of designing the product life cycle through choices about product concept, structure, materials and processes, and *life cycle assessment* (LCA) is the tool that visualizes the environmental and resource consequences of these choices. The ability of LCAs to measure the environmental impact of a product throughout its life cycle, makes them a unique holistic tool for assessing the environmental and resource consequences of choices made in product development (13). Along with sets of guidelines to improved environmental performance LCAs make up the modern tool-kit of environmentally conscious product development (14).

Product stewardship schemes dealing with complex products have been initiated by a growing number of predominantly larger manufacturers of electronics and cars in the past three years, including Hewlett-Packard (waste reduction and materials conservation, energy efficiency and end-of-life issues of printers and personal computers) (15,16), AT&T (methodology development and pilot study of a business phone) (17,18), IBM (LCA pilot study of disc drives and end-of-life and energy efficiency issues of personal computers) (19,20), Digital (LCA methodology and studies on components) (21) and Xerox (end-of-life issues of User Interface Modules) (22) in the US, Siemens (end-of-life issues for various products) (23), Daimler-Benz (methodology and LCA pilot on vacuum cleaner) (24) and Loewe-Opta (broad array of life cycle issues for a CTV) (25) in Germany, Philips (broad array of life cycle issues for various products) (26) in the Netherlands, Fiat (LCA pilot on a block engine) (27) in Italy, ABB (large-scale EMS program) (28), Ericsson (LCA pilot on radio systems) (29) and Volvo (methodology) in Sweden, Danfoss, Bang & Olufsen and others in Denmark (methodology and LCA pilots on electro-mechanical products, refrigerator, CTV and high-pressure cleaner) (13), and many more.

2.3 Overview of design strategies

The diagnosis of environmental problems on the basis of environmental profiles is a key activity in making full use of LCA as a tool in product development. A successful diagnosis is the result of a team work between LCA practitioners and designers, and it should result in the identification of so-called *improvement potentials*.

Improvement potentials may be deduced from the environmental profile as those changes in product concept, structure and/or components that lead to the greatest improvements in environmental performance. Improvement potentials may vary amongst product types, but they generally correspond to one or more of five overall improvement strategies: better material handling, chemical savings or substitutions, thermal energy savings, electricity savings and overhead reduction (13). (Overhead is the common term for environmental burdens from the operations of a company not directly related to the manufacture of products, such as ventilation, heating of buildings etc.) Contributions to environmental effects in any given life cycle phase may be divided between these five sources only.

A real-life design strategy for improved environmental performance has its basis in the technological possibilities for innovations in product concept and/or structure, and in material and process alternatives. As a starting point only the products functionality is in principle fixed, and the realization of this functionality may be done in numerous ways. Most of the environmental parameters and the actual life cycle of the product are indeed fixed by the choices of product concept and structure. Rather than talking about product life cycle design at this stage, we should talk about the design of product life cycles. To appreciate that the life cycle engineer has influence on the choices about product concept and structure is essential to take full advantage of a product stewardship initiative.

Only when environmentally conscious choices about product concept and structure are made, and the overall design strategy is fixed, does it make true sense to implement design strategies dealing with construction materials and manufacturing processes. This is a, definitely relevant, issue of system adaptation, since many of the choices about materials and processes are already made by choosing an overall design strategy.

The overall and subsequent design strategies most often pursued in life cycle design are listed in table 1, under a heading giving the life cycle phase they report to. "Design strategy" is taken in the broad sense of the term to include environmentally beneficial strategies related to but not directly involving the product.

Design strategies reporting to the pre-manufacture phase deals with the environmentally conscious selection of materials and components. Materials are roughly divided into renewable materials, not subject to ultimate depletion, and non-renewable materials subject to depletion. From a resource depletion point of view, renewable materials are generally to prefer over non-renewable, however, keeping an eye on the trade off in impacts on the external environment. This latter consideration is prevalent in choosing materials with small environmental rucksacks, i.e. materials that cause the lower impacts on the external environment in the production of the material from natural resources. Because the production of recycled materials generally is less polluting than the production of virgin materials, recycled materials are to be preferred. Choosing a suitable construction material is most often a case of system adaptation.

Life cycle phase	
Pre-manufacture	
Strategy	**Relevance**
Use of recycled materials	Resource depletion, environmental burdens
Use of less energy intensive materials	Environmental burdens
Environmentally conscious component selection	Supplier performance, environmental burdens
Use of renewable materials	Resource depletion
Manufacture	
Use high-throughput processes	Environmental burdens, working environment
Use material saving processes	Resource depletion, Environmental burdens
Overhead reduction	Environmental burdens
Transportation/distribution	
Improved logistics	Environmental burdens
Low volume/ weight	Environmental burdens
Use recycled materials for packaging	Resource depletion, environmental burdens
Use	
Low energy consumption	Resource depletion, environmental burdens
Design for maintenance/ long life	Resource depletion
Disposal	
Design for disassembly	Resource depletion
Material quality preservation	Resource depletion, environmental burdens

Table 1 Prevailing design strategies.

The manufacture of components and sub-assemblies, not actually performed by the product manufacturer, is part of the pre-manufacture phase. In the short run, the product manufacturer can only influence the environmental performance of pre-manufacture by choosing those components and subassemblies with the lower environmental burdens attached. In the long run, however, major stakeholders may put demands on the suppliers environmental performance, and thus influence the environmental performance of their own products.

Design strategies reporting to the manufacture phase deals with either improving process performance or with reducing overhead. Close studies of environmentally relevant manufacturing processes reveal that the environmental burden per unit manufactured depends closely on through-put time, since many of the polluting processes run continuously and the total environmental burden is proportional to the time the process is on. Hence a successful strategy is to increase throughput, thus reducing the burden per unit. Another prevailing strategy is to design for the use of material saving processes, both because the material lost is associated with pre-manufacture burdens and because the very loss of material puts unnecessary strain on natural resources.

To reduce overhead is not a product design strategy strictly speaking, but since overhead is distributed over the total number of units produced, a reduction in overhead means a more environmentally friendly product. In practice reducing overhead means reducing the consumption of energy, the production of energy being polluting and consuming energy resources.

Design strategies reporting to the transportation phase are either directly connected to the product, such as design for low volume or weight and the choice of environmentally friendly packaging materials, or to operational practices, such as the improvement of transport logistics. Since the energy consumption (and cost) of many transportation processes are related to the weight or volume of the product, reducing these will result in a more environmentally friendly product.

Packaging is becoming a focus area, as packaging makes up a substantial part of the municipal waste stream. Packaging initiatives include using recycled material for packaging, such as cardboard, or recyclable material, such as EPS (expandable polystyrene) (32). But also making the product itself less fragile can result in substantial savings in both materials and cost. Digital Equipment Corporation has done such a study, where the fragility of internal storage elements for computers was reduced to render a packaging material reduction of 54 % and a packaging cost reduction of 62 % (30).

Design strategies reporting to the use phase deals with increasing functional efficiency, adaptation to individual use patterns, and reduction of the consumption of consumables, primarily energy. Increasing functional efficiency means to increase the number of so-called functional units of the product, e.g. the number of hours of activity of a TV set. A major strategy is to prolong product life, thus decreasing those environmental burdens per unit that are not proportional to the number of functional units. This involves to design for maintenance and serviceability, e.g. by a modular construction principle. The consumption of consumables in the use of a given product may be highly individual, and progress may be made by analyzing and identifying individual use patterns and design accordingly.

In designing for the disposal phase, two major principles prevail. Firstly, adaptation to current and future disposal systems. This involves the discipline of design for disassembly, which enhances recovery efficiency. Secondly, the issue of material quality preservation is essential. It is well known that the removal of impurities in the reclamation of metals is associated with the larger part of the environmental burdens, and recent research confirms this (33). Further, high purity is absolutely essential in the direct recycling of plastics (34). A growing number of corporations now put focus on recycling in their design activities, f.i. Ricoh Corporation focuses on use of recycled materials and marking of plastic parts (73),(74).

2.4 Design for low energy consumption in the use phase and design for disassembly

Two design strategies deserve special attention, design for energy savings in the use phase (DfES) and design for disassembly (DfD), because of their widespread implementation, and because they take action on some of the most important environmental issues, namely the depletion of energy resources, the pollution from the production of energy, the preservation of pools of non-renewable resources through recycling, and the pollution savings from using recycled materials.

Let's first turn to DfES. LCA studies of active products, i.e. products that consume fossil fuels or electricity during operation, have shown that large parts of the contributions to the total overall environmental impact stem from the consumption of energy in the use phase. This is particularly true for electronic and automotive products. In the case of the TV set in figure 5, 80 % of the total contribution to global warming comes from the use of electricity in the use phase (35). A study of a hand portable telephone states that 39 % of the total global warming impact comes from the use phase (14). Similar trends are seen in acidification potentials and the toxicity to eco-systems. So it's easy to see that contemporary active products do have a large impact on the environment during use.

Until recently the use phase energy consumption has not been a parameter in consumer preference, and consequently little attention has been paid to this rather large improvement potential. This is changing. It is now commonplace for e.g. manufacturers of white goods to use the cost savings in use due to reduced consumables requirements as a marketing feature. Consumer preference along with corporate environmental policies are expected to be the major driving forces in reducing use phase energy requirements of active products. However, also purely technological needs may lead to the same result. E.g. the widespread need to make the most of batteries has led to significant improvements in energy requirements of certain products (36).

Government initiatives are also expected to be an incentive for improvement. In 1992 the US-EPA initiated its well know Energy Star eco-labelling program, awarding the label to e.g. computers with idle time energy consumptions below 30 watts (37). The fact that the US government now only purchases computer equipment with the Energy Star label has helped to push 180 PC and monitor manufacturers to be certified as of January 1994 (38) - a significant success. By the year 2000 the Energy Star and other programs are expected to save 26 billion kWh a year in the USA, eliminating the need for 10 power stations (39).

Reduced energy requirement may be achieved by one or both of two general strategies: reduced actual effect use and reduced stand-by requirements. Looking at electronic products the power supply is a focus of attention in both strategies (36). Traditional power supply systems consist of a transformer, a rectifier and a linear voltage regulator. The key word is efficiency, a typical efficiency of a transformer is 70 % or lower, for a linear voltage regulator 50 % or lower and for a rectifier around 90 %. This lack of efficiency causes energy loss in the very process of supplying the device with electrical power. A new type of power supply is on the market, the switch mode power supply (SMPS), eliminating the regulator, and with an efficiency of around 80 %, but with the potential for further improvement. The SMPS is, although beneficial from an environmental point of view, in some uses a relatively unproven technology and some manufacturers shrink back from using it.

Color TV-sets are a focus area of technological improvement with regard to energy consumption in the use phase. Several manufacturers are actively putting new environmentally friendly CTVs on the market. Contemporary high-end 28" CTVs with Nicam etc. have an in use power consumption of 70 to 120 watts (35), of which about two thirds are used for the cathode ray tube. Reductions in in-use consumption of about 10 % is achievable by using e.g. new power supply technology, but a substantial improvement awaits a quantum leap in display technology (35).

Refrigerators are another focus area. A contemporary average size (300 liter) refrigerator uses about 35 watts on average, with stand-by energy consumptions of about 1 watt, and the major energy use for cooling. About 75 % of the energy is lost due to heat transfer and only about 25 % is actually used for cooling goods and volume after the refrigerator has been opened. Two overall strategies are pursued in reducing the energy consumption: better insulation and higher efficiency of the cooling system. By using more insulation material, the heat loss is reduced at the expense of cooling volume. To counter-act this low energy refrigerators are usually taller than conventional models. In the long term significant improvement may result from switching to insulating vacuum panels. Concerning the low efficiency of current models, focus is on the cooling system. A conventional cooling system consists of a compressor, a condenser and an evaporator. The motor for the compressor has a low efficiency, giving the compression action an efficiency of about 40 %. New motor designs, f.i. motors with permanent magnets, are explored. Concerning the rest of the cooling technique, the low efficiency is due to the large temperature difference between device and cooling medium. Improvements may be achieved by means of forced convection or by using larger areas for heat transfer. It is expected that these improvements will result in a low energy refrigerator, using about 20 watts for a typical 300 liter size (40).

The fact that so many of the devices we use today are active all 24 hours of the day, puts focus on stand-by consumption. Although stand-by or idle mode effect consumptions are much lower than in-use effect consumptions, the total stand-by energy consumption make up a great part of the energy used by the product. A telephone answering machine is a classical example - it is in use probably less than one percent of the time, and even a TV-set with a stand-by effect of a few percent of the in-use effect may attribute 25-30 % of its power consumption to the typically 19 hours of stand-by time a day (41). Newest innovations in CTV stand-by technology have achieved a stand-by consumption share of about 10 % with a substantial reduction in stand-by energy consumption (35).

As landfill sites are becoming scarce in the industrialized countries, waste reduction is becoming a focus area in product development as well. Manufacturers are becoming responsible for their products also in the disposal life cycle phase, and the rising costs of landfill, which in the end is borne by the consumer, must be reduced. Lower disposal costs are expected to become a sales parameter, as new legislation mandating the take-back and environmentally safe disposal of consumer products are coming into force in the nineties, as e.g. the German Electronic Scrap Ordinance (42). Key issues are disposal costs and recycling efficiency. Although focus was initially put on the end-of-life phase by the need to reduce landfill volumes, higher recycling rates preserving natural resources and recycled materials with smaller environmental rucksacks are beneficial spin-offs with key relevance to the development of sustainable societies. Recycling does indeed play an important role in the dynamics of non-renewable resource flows (43).

In order to meet the new demand for recyclable products, the life cycle discipline design for disassembly (DfD) has gained considerable momentum in the last few years (44). The possibility to disassemble products into recyclable fractions and the issue of material quality preservation is the heart of the matter in optimal recycling. Current products are designed for easy assembly and cost-effective use of construction materials, with focus only on manufacture - it has not been commonplace to take the disposal phase into account, since disposal costs traditionally have been paid by the society as a whole and not by the individual consumer. This practice has resulted in products less suited for disassembly. The main problems with current consumer products are that it takes a lot of disassembly steps to take them apart, that joining techniques are directed towards assembly and not disassembly, that the optimization of cost-effectiveness in the use of construction materials has resulted in large material diversity and complex sub-assemblies, that environmentally problematic components are dispersed throughout the product, often at a considerable disassembly depth and that product configurations do not take into account the effects of e.g. corrosion, which are highly problematic to a disassembly operation. These are the barriers to disassembly found in current products. However, a few other considerations are also connected to DfD, e.g. that disassembly friendly products are easy to handle and that they do not constitute a hazard to occupational health.

Benefits	Design rules
Less disassembly work	- Combine elements - Limit material variability - Use compatible materials - Group harmful materials into subassemblies - Provide easy access to harmful, valuable or 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 colors 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

Table 2 Generally accepted DfD design rules (44).

Designing for disassembly involves the use of general design rules and various tools. We discuss the tools in a later section, and in table 2 an overview of generally accepted design rules is shown (44,45).

Less disassembly work is achieved by decreased and cost-effective disassembly depth and subsequent sorting of parts into recyclable fractions. Important design guidelines are parts consolidation e.g. to reduce the number of parts and subassemblies of the product, material variability limitation - using a decreased number of (recyclable) construction materials (alternatively to only join compatible materials), clustering of e.g. harmful components into the same subassembly and to facilitate easy access to harmful, valuable or reusable parts or components.

Disassembly depth often displays a cost effective optimum, where further disassembly and the disposal of the remainder costs more than is gained by selling the disassembled parts. Figure 2 shows this basic relationship.

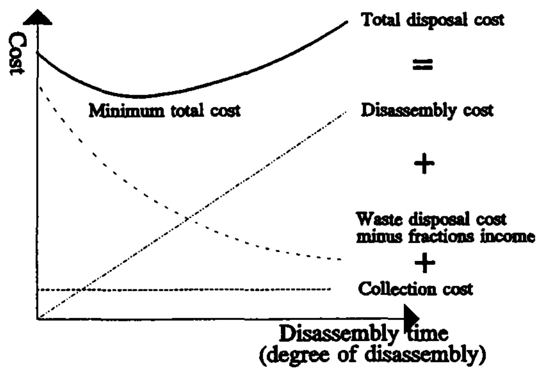

Figure 2 Total cost of disposal in a disassembly scenario (46).

When a product enters a disassembly station it may no longer be exactly the product that was initially manufactured. During its life time a product is subject to repair, contamination and corrosion, and these factors make disassembly a less easy task. Important design guidelines in this context are to avoid the combination of materials that may give rise to corrosion or ageing and to protect parts against dirt and corrosion.

As the very process of disassembly is manual today (and presumably automatic in the future), to design the product for ease of disassembly is of key importance. Guidelines to this end include to facilitate easy drainage of product fluids, to use disassemblyfriendly fasteningtechniques (easy accessibility, low disassembly forces, no adhesives, minimum number of fasteners, multiple fastening of stacks of components), to design for simple disassembly movements e.g. no rotations, stacked construction (essential for automated disassembly) and to avoid metal inserts in plastic parts.

Easy product handling is an issue related to automation and working environment. This involves to provide grips for robots, to use rigid parts and to seal off hazardous substances.

During the disassembly operation parts are to be separated into recyclable fractions. This involves to avoid in-compatible complex parts and to design for material recognition, be it by means of labels, codes or otherwise. Since the remainder of the product and some disassembly fractions are often shredded for metal recovery after disassembly, it is important to avoid the use of materials a shredder cannot cope with and to avoid using materials that a shredder-based operation cannot recover.

To reduce manipulation costs of automated disassembly it is important to use standard parts and to reduce the number of different joining elements.

3. Life cycle design methods and tools

3.1. LCA methods and tools

A product LCA has four basic elements: scoping and goal definition, inventory, impact assessmentand evaluation of results (47). In the goal definition, the scope of the study is determined, including such factors as the choosing of a functional unit that the environmental performance is measured against, the identification of the life cycle looked at and the setting of system boundaries. In the inventory stage, all environmentally relevant inputs and outputs to the processes making up the life cycle in focus are quantified, yielding a collection of baseline data for material and energy consumption and emissions to air, water and soil. These baseline data are subsequently translated into measures of the impact on the environment caused by the product in the impact assessment. Finally, an evaluation of the severeness of these impacts is performed. While there is a general consensus on how to perform the two first stages, several impact assessmentmethods and evaluation methods exist, however, all impact assessment methods give a quantitative measure of the contributions to the most problematic environmental effects, some including chemical working environment and the draw on natural resources. An excellent discussion of the individual steps in product LCA is given in (71) and (72).

The principal steps in the application of LCAs and environmental guidelines in product development are shown in figure 3 (48). The product development process is divided into seven distinct phases, idea generation, analysis, goal definition, development, detailed design, establishment of production and actual production, all with their special tool requirements. The figure further shows the five major fields of activities within a successful environmentally conscious product development process: to synthesize the product, to model the products life cycle, to identify focus areas and improvement potentials, to specify design goals and to verify that the goals are met. Going through the figure in spiral-like motions from top left to bottom right takes you through the development procedure.

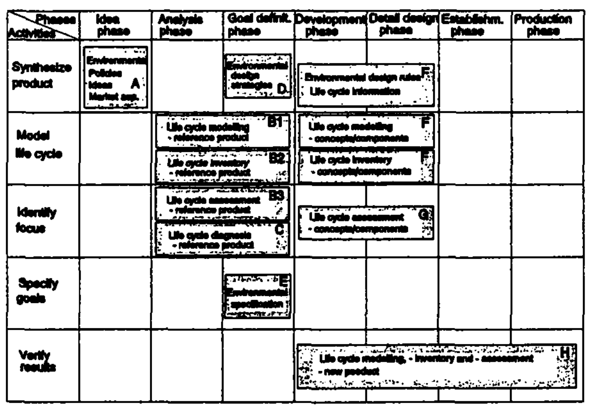

Figure 3 Environmentally conscious product development(48).

Life cycle assessments are used throughout the development procedure, initially on a so-called reference product - an own or competing product that has the same basic functionality and/or technology as the product target of the development effort (B). This initial full-blown LCA applied in the analysis and goal definition phases reveals the good and bad environmental features of the reference product and it is possible to identify improvement potentials, focus points and subsequently design strategies (C,D). This leads on to an environmental product specification (E). In the actual development and detailed design phases LCAs may be used to model and identify the environmental performance of various concepts for the product itself or subassemblies (G), also using sets of environmental guidelines (F). This is where the actual choices about construction materials and manufacturing processes are made, taking into account the total life cycle performance of the relevant options. Modelling the environmental consequences of the relevant design options eventually leads to the conceptual and structural detailed design of the product, after which it is possible to establish production. And at which time it is possible to perform yet another full-blown LCA (H) to see if initial goals for environmental performance are met, and which may serve partly as the basis for the work with the next product generation.

The output from an LCA is the environmental profile, quantitatively stating the potential or actual impact on the environment from the product or subassembly life cycles. An environmental profile for the use in product development has to have two key features. Firstly, it should clearly state all the relevant impacts on the environment, global impacts as well as regional and local ones. The relevant environmental effects include global warming, stratospheric ozone depletion, acidification of land and water eco-systems, photochemical ozone formation (smog), nutrient enrichment in freshwater and marine eco-systems, the toxicity towards humans and eco-systems and solid waste generation. Also issues of resource draw/depletion and working environment should be addressed. Further, it is important that the environmental profile holds information about where the contributions to the total impact come from, so that it is possible to trace the origins of the environmental problems to the use of e.g. certain materials or manufacturing processes. In figures 4 and 5 examples are shown of environmental profiles suited for use in product development.

Table 3 gives an overview of the various tools and methods used worldwide for LCA studies of complex products. The list is extensive, however, presumably not exhaustive.

One of the earliest tools is the Boustead Model, which is essentially an inventory tool without an impact assessment feature. The tool has a database with data on approx. 4000 unit operations, including energy production scenarios for all OECD countries, transport processes and material processing for various organic and inorganic materials (49). The tool has been used on various complex products, f.i. in the automotive industry (50).

Tool	Developed by	Type	Used on complex products	Impact assessment	Database available
Boustead Model	Boustead Consulting (UK)	Quantitative tool	Yes	No	Yes
LCA inventory Tool	Chalmers Industriteknik (S)	Quantitative tool	Yes	No	Yes
LiMS	Chem Systems (USA)	Quantitative tool	?	?	Yes
TEAM	Eco-bilan (F)	Quantitative tool	Yes	Yes	Yes
GaBi	Institute for Polymer Testing and Science - IPK (D)	Quantitative tool	Yes	Yes	Yes
Eco-Pro	EMPA (CH)	Quantitative tool	?	Yes	Yes
LMS Eco. inv. tool	LMS Umweltsysteme (A)	Quantitative tool	?	?	Yes
Oeko-base	Migros (CH)	Quantitative tool	No	Yes	Yes
PEMS	PIRA International (UK)	Quantitative tool	Yes	Yes	Yes
EcoAssessor	PIRA International (UK)	Quantitative tool	?	Yes	Yes
SimaPro	Pré Consulting (NL)	Quantitative tool	Yes	Yes	Yes
PIA	Instituut voor Toegepaste Milieu-Economie (NL)	Quantitative tool	Yes	Yes	Yes
IDEA	VTT (SF)	Quantitative tool	Yes	Yes	Yes
EDIP-tool	Institute for Product Development (DK)	Quantitative tool	Yes	Yes	Yes
EPS-tool	Swedish Environmental Research Institute - IVL (S)	Quantitative tool	Yes	Yes	?
CUMPAN	Daimler-Benz (D)	Quantitative tool	Yes	Yes	Yes
Matrix approach	AT&T (USA)	Semi-quantitative method	Yes	No	No
Pre-LCA Tool	Battelle/Digital (USA)	Semi-quantitative method	Yes	No	No

Table 3 Overview of LCA tools and methods.

The LCA inventory Tool from Chalmers Industriteknik in Sweden, is, as the name states, an inventory tool without an impact assessment feature. Featuring a database with data on energy and transport issues along with some manufacturing processes, the tool has been used on complex products, f.i. a refrigerator (49,51).

The french TEAM tool from Ecobilan is like all the above a full quantitative tool, featuring both a database and an impact assessment function (49). The tool has been used on complex products (52).

Similarly for the GaBi tool from IPK in Germany, which is available also in German language (most tools available in English language), and has a database with 350 processes from chemical, metallurgical and polymer industries (49).

Also the Eco-Pro tool from EMPA in Switzerland is available in German language. This tool has focus on packaging materials, and it is not clear whether it has been used on complex products, but it does feature an impact assessment function.

The Austrian LMS inventory tool features a database, however, it is not clear to the authors whether it has indeed been used on complex products or whether it has an impact assessment feature.

The Oeko-Base für Windows from Migros in Switzerland is only available in German language. It has an extensive database on packaging materials with data from or relating to Switzerland (49). It has not been used on complex products. It does, however, feature an impact assessment function.

PIRA International in the UK has put yet another full quantitative tool in the market, the PEMS tool, featuring an impact assessment function and a database with over 150 entries for a range of packaging materials (49). The tool has been used on complex products. PIRA further markets a less extensive tool, the EcoAssessor for users wanting a simplified tool (49).

One of the quite few tools directly intended for use on complex products is the Dutch SimaPro tool in version three. The tool is quantitative and has a detailed impact assessment function, making it easy for engineers with no or little environmental knowledge to relate to the output. An example of the SimaPro output for a coffee maker is reproduced in figure 4.

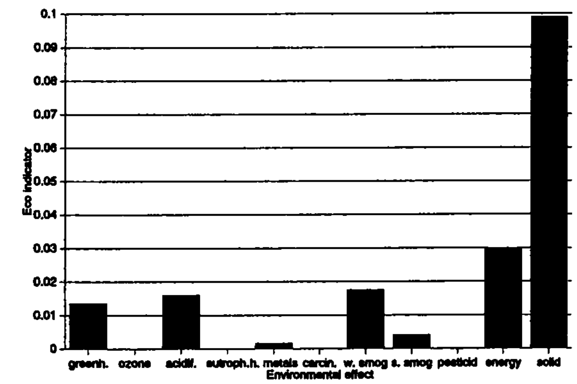

Figure 4 Environmental profile for a coffee maker. Example of output from SimaPro3, reproduced from (53).

The Dutch PIA tool has similar characteristics as the SimaPro tool.

Another tool well suited for use in product development of complex products is the Finnish IDEA tool from VTT. The tool features database and impact assessment options, and has been used on complex products (54).

The same goes for the Danish EDIP-Tool, which was developed entirely for the use on complex products. The tool which is in the Danish language has been tested on a number of complex products in Denmark, including a CTV and a refrigerator. The tool has an impact assessment feature, resulting in a detailed output, which also shows where the major contributions to the various environmental effects come from. An example of the EDIP output is given in figure 5.

The Swedish EPS tool was also initially developed for the use on complex products, and it features an impact assessment function, however, it is not clear if the tool has a database. The tool has been used on complex products (55).

Daimler-Benz in Germany uses the CUMPAN tool of their own development, which features both database and impact

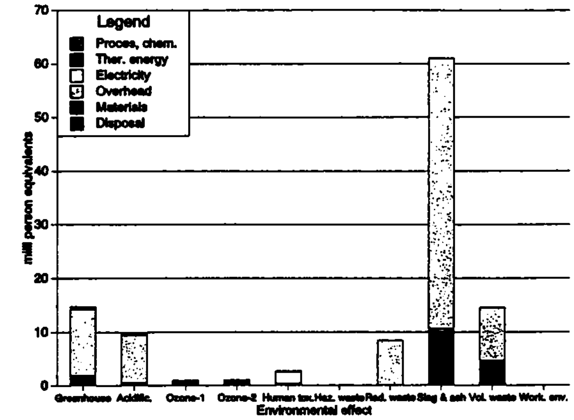

Figure 5 Environmental profile for a color TV set. Example of output from the EDIP-tool, reproduced (35).

assessment function. Some of the impact assessment methodology is similar to the EDIP-Tool (24).

All the above are full quantitative tools taking as calculation inputs real-life inventory values for emissions etc. There are, however, some semi-quantitative or pre-LCA tools in use, applying a score system to quantify key life cycle parameters. Two such are mentioned in table 3, namely the Matrix Approach suggested by AT&T (18) and the so-called pre-LCA Tool suggested by Battelle and Digital (21). Semi-quantitative tools are fast but crude, and largely rely on the direct subjective assessment of environmental severeness of product related environmental parameters. They provide a starting point for environmentally conscious product development, but they do not allow for the more complex design of product life cycles.

3.2 DfD Methods and Tools

Whereas the choices about materials and processes are laid out in the application of the holistic life cycle assessment methodology, DfD methods and tools focus on product structure in order to ease disassembly (decrease disassembly time) and to put together product parts that require the same route of disposal (56). The emphasis is on disassembly and recycling cost and efficiency - DfD methods and tools catalyze this process and enhance recycling rates. LCA and DfD supplement each other with respect to the planning of the disposal life cycle phase.

The number of methods and tools suggested by universities and companies is quite large, and we cannot hope to fully exhaust the issue in this paper. However, we shall discuss a few methods and tools along with relevant case studies. A good overview is given in (57). Universities in Germany are particularly active in the development of methods and tools to support design for disassembly, some key activities are those of Seliger and group in Berlin (45,58,59,60,61), Krause and group in Berlin (62), Weule, Spath and group in Karlsruhe (63,64), and many more. Further, some activity is taking place in USA, where computer-based tools are under development, such as the ReStar tool of Carnegie-Mellon University, Pittsburgh (65), and the LASeR tool of the Ohio State University, Columbus (66).

One or both of two features are present in all DfD methods and tools, namely the grouping of parts into subassemblies with fixed disposal requirements and the calculation of the optimum disassembly depth. There are two basic problems in designing for the end-of-life phase, namely that it's a multiple objectives task and that the product is in fact designed for a future disposal scenario, of which we have only indications today. A German study suggests the use of utility theory integrating probabilistic engineering design to resolve these issues (58). The study uses utility theory to assess the optimal disassembly sequence under assumptions of different future disposal scenarios. Making use of so-called AND/OR graphs for representation of the technically feasible disassembly sequences, the problem is transformed into a computer-based graph search problem. Using a washing machine subassembly as a case, it is clearly shown that increases in material value and/or dumping fees result in different optimal disassembly sequences.

The use of recycling or recovery graphs for optimizing disassembly depth is at the center of most DfD applications. These graphs are generally a representation of the product structure in terms of nodes representing parts or components connected with strings representing a disjoining operation. One example of a recovery graph for a cathode ray tube (CRT) is shown in figure 6 (59).

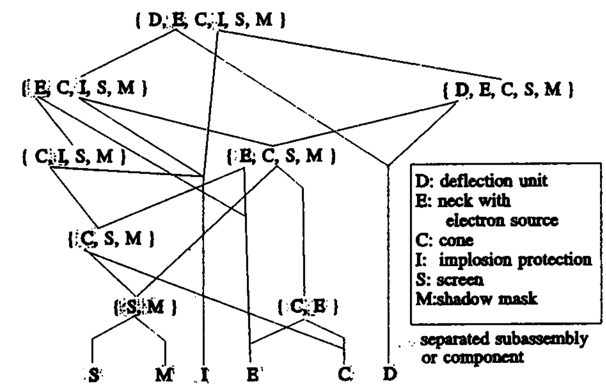

Figure 6. A recovery graph for a CRT (59).

Another computer-based tool is the Recyclinggraph Tool developed at the University in Erlangen (67). The tool supports the determination of the number of economic disassembly steps and the optimum recycling strategy. Using the Recyclinggraph editor (Regred), the possible product structures are given as inputs along with information about the connections of components and components weights and material compositions. Subsequently recycling groups are formed of parts which require the same recycling strategy. The tool operates with five strategies: component recycling, material recycling, incineration and the landfill of either hazardous components or not hazardous components with little value. Various product layouts may be compared using an evaluation methodology focusing on some ten key issues and allocating a score for each issue.

Focus is also on recycling groups in the ABC method of IWB, Munich (68). Subassemblies are divided into subassemblies for reuse (category A, high manufacturing costs, long lifetimes and long innovation cycles), subassemblies for special processing (category B, complex mixtures, short lifetimes and short innovation cycles) and subassemblies for material recycling with existing technology (category C, low production costs, big volumes or high material costs). This method basically supports the choice of recycling strategy by simplifying product structure, and it has been tried out on an electric saw case with a good result concerning both assembly and disassembly, as shown in figure 7.

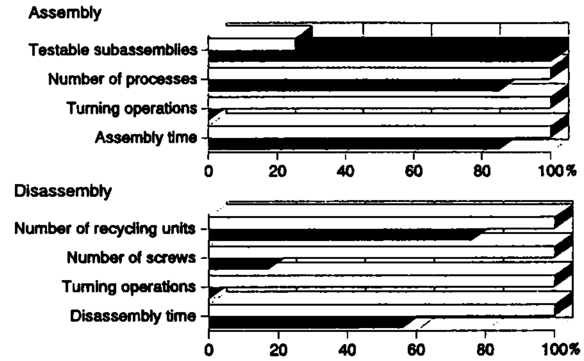

Figure 7. Applying the ABC method to an electric saw (68) Old design: white bars. New design: black bars.

4. Implementation of tools

The number of tools on the market is large and growing as the market develops. It is a difficult task to choose between tools when entering into life cycle engineering, but good tools are essential to keep time for calculation work at an acceptable level. A good LCA tool can be used for modelling life cycles, as well as for inventory and impact assessment. That the tool offers one or a selection of impact assessment options is often a necessity because the product development team cannot easily relate to the result of an inventory, which is basically a list of material and energy consumptions and emissions.

To reduce calculation time an extensive database is further necessary. A database has to be supplemented and customized, because it is important that site-specific real-life data are used to get a true up-to-date LCA result. This means that data for the acquisition of those exact raw materials that the company uses should be provided, preferably from the true up-steam sources. It further means to collect data on energy and material consumption as well as emission data from suppliers, to measure those same characteristics of in-house manufacturing processes, and not least to have a good knowledge about the individual use patterns of consumers. Finally, detailed knowledge and data on the product specific disposal/recycling processes are essential.

A customized database has to be kept up-to-date, which requires a certain training of personnel in basic environmental knowledge and data handling. In fact to use new environmental tools requires extensive training of the company's product development function with regard to environmental effects, where they come from and how they impact on the environment. Trade-offs will occur between environmental impacts in the environmental profile of the product, and the development team should be aware of the environmental consequences of these trade-offs. Aggregating impact assessment numbers for different environmental effects into one single environmental indicator for the product by means of f.i. e weighing system, is, however tempting, the classical controversy of 'comparing apples and oranges', and cannot be recommended. Training and education of the work force is a cornerstone in any product stewardship initiative, as also reflected by the ABB action plan in figure 1.

Pilot studies have preceded the full-scale establishment of life cycle engineering schemes in most companies. To choose a product or subassembly case for a pilot study is to choose with care. The case has to be simple yet representative of the materials and technology generally used in the company, it has to have relevance also in future markets, it is preferably well-known to the company, and further work would benefit from a short innovation cycle. A pilot study is essential to gain insight into the possibilities and limitations of environmental tools, in order also to overcome barriers and fears such as the possibility of increased product cost and the prolongation of product development time due to environmentally driven solutions.

Further, as product related environmental issues are new to most companies, in-house standards and guidelines are not available. The development of such standards and guidelines is essential to support the efficient use of environmental tools.

5. Outlook

The challenges that await us are manyfold. First and foremost a change in perception is needed to put emphasis on the holistic quality of life cycle engineering, through interdisciplinary cooperation between politicians, economists, scientists and engineers. We are facing a change in the whole concept of industrial production and in our attitude towards the consumer society, mandated not only by profound demographic end economic evolutions, but also by a growing consumer awareness of environmental issues.

Consumer awareness and not least the growing pressure from grass roots and NGOs is changing the citizens attitude towards industry. Only those companies with a clear view on this can hope for a continued prosperity. The 'eco-factory' may be the future where a sustainable industry produces environmentally friendly products for a sustainable society.

And this does not only hold true for the manufacturing industry. The life cycle concept will gradually disseminate into other industries, like the food industry, the textile industry and the building industry. And focus may shift to the environmental impacts from the life cycle of facilities, as is seen today in Japan (69,70). We will see a growing focus on also small and medium-size companies, where a business-line approach to the organization of life cycle engineering initiatives may prevail.

One important area of future activity is the internalization of environmental externalities in cost calculations. The life cycle cost concept includes the costs of environmental impacts into the overall cost balance, thus allowing for e.g. the inclusion of pollution penalties in product cost calculations (75),(76).

To save precious natural resources, product end-of-life design initiatives along with increased technological development in the recycling industry will bring about closed anthropogenetic material flows, where we reutilize natural resources again and again. To facilitate this we not only need a widespread use of DfD methods and tools, but we also need to focus on new materials, new coating technologies and new processes that can handle the recycling of complex mixtures of materials.

Life cycle engineering, the discipline of handling the new environmental parameter in product design, now has a stronghold in the manufacturing industry.

References

(1) See f.i. Weterings, R.A.P.M., Opschoor, J.B., 1992, "The Ecocapacity as a challenge to Technological Development", RMNO Publication No. 74a, The Netherlands.
(2) "Our Common Future", 1987, World Commission on Environment and Development, Oxford University Press.
(3) Alting, L., Jørgensen, J., 1993, "The Life Cycle Concept as a Basis for Sustainable Industrial Production", Annals of the CIRP, vol. 42, No. 1, pp. 163-167.
(4) "Earth Summit - Agenda 21. The United Nations Programme of Action from Rio", 1993, published by United Nations.
(5) Alting, L., 1991, "Life Cycle Design", Concurrent Engineering: Issues, Practice and Technology, vol. 1, No. 6, pp. 19-27.
(6) Alting, L., 1993, "Designing for a Lifetime", Manufacturing Breakthrough, May/June edition, pp. 29-33.
(7) See f.i. Benjamin, Y., 1994, "An Introduction to the United Nations Environmental Program Working Group on Sustainable Product Development", published by UNEP-WG-SPD at the University of Amsterdam, The Netherlands.
(8) Schmidheiny, S., (ed), 1992, "Changing Course", The MIT Press, Cambridge, USA.
(9) "BS 7750 - Specification for Environmental Management Systems", 1992, British Standard.
(10) EMAS standard according to the EEC Council Order No. 1836, 1993.
(11) ISO/CD 14000 (Committee Draft), 1994, "Environmental Management Systems - General Guidelines on Principles, Systems and Supporting Techniques", International Standard Organization.
(12) "ABB Environmental Management Program - Initial Review", 1994, published by Asea Brown Boveri Ltd., Stockholm, Sweden.
(13) Wenzel, H., Hauschild, M., Jørgensen, J., Alting, L., 1994, "Environmental Tools in Product Development", Proceedings of the 1994 IEEE International Symposium on Electronics & the Environment", San Francisco, pp. 100-108.
(14) Legarth, J.B., Alting, L., Erichsen, H., Gregersen, J., Jørgensen, J., 1994, "Development of Environmental Guidelines for Electronic Appliances", ibid, pp. 69-74.
(15) Bast, C., 1994, "Hewlett-Packard's Approach to Creating a Life Cycle Program", ibid, pp. 31-36.
(16) Korpalski, T., 1994, "Pragmatic Use of Priority Life Cycle Assessment Elements to Help Drive Product Stewardship", ibid, pp. 207-210.
(17) Keoleian, G.A., Glantschnig, W.J., McCann, W., 1994, "Life Cycle Design: AT&T Demonstration Project", ibid, pp. 135A-135H.
(18) Graedel, T.E., Allenby, B.R., Comnie, P.R., 1995, "Matrix Approaches to Abridged Life Cycle Assessment", Environmental Science and Technology, vol. 29, No. 3, pp. 134-139.
(19) Kaiser, L., 1994, "Green Hardware Development Process", Proceedings of the 1994 IEEE International Symposium on Electronics & the Environment", San Francisco, pp. 121-127.
(20) Young, W.S., Andersen, J.J., 1994, "Environmentally-Conscious Disc Drives", ibid, pp. 273-278.
(21) Tolle, D., Vigon, B., Salem, M., Becker, J., Salveta, K., Cembrola, R., 1994, "Development and Assessment of a Pre-LCA Tool", ibid, pp. 201-206.
(22) Seaver, W.B., 1994, "Design Considerations for Remanufacturability, Recyclability and Reusability of User Interface Modules", ibid, pp. 241-245.
(23) Ebach, H., 1994, "Advanced Dismantling Systems, an Important Step in Life Cycle", Proceedings of the CIRP 2. International Seminar on Life Cycle Engineering, Erlangen, pp. 267-276.
(24) Zürn, J., Diener, J., 1994, "Ecological Assessment of Products and Processes - Challenge and Opportunity", ibid, pp. 18-33.
(25) Schaas, 1994, "Design of a Recyclable TV-set", ibid, pp. 149-153.
(26) Stevels, A.N.L., 1995, "Strategic Environment-Orientated Product Development", paper presented at the conference Recycling of Electro-mechanical Products, Haifa, Israel, April 1995.

(27) Baldo, G.-L., 1995, University of Turin, Italy, personal communication.
(28) "Products & Plants and Suppliers", 1994, published by Asea Brown Boveri Ltd., Stockholm, Sweden.
(29) Bundgaard, H., L.M.Ericsson, Stockholm, Sweden, personal communication.
(30) Nielsen, L., 1994, "Reducing Material Use in Protective Packaging for Computer products", Proceedings of the 1994 IEEE International Symposium on Electronics & the Environment, San Francisco, pp. 317-322.
(32) "Environmental Protection in the Computer Industry", information material from Hewlett-Packard.
(33) Legarth, J.B., Alting, L., 1995, "Sustainability Issues in Circuit Board Recycling", Proceedings of the 1995 IEEE International Symposium on Electronics & the Environment, Orlando, pp. 126-131.
(34) Mølgaard, C., 1995, "Environmental Impacts by Disposal of Plastic from Municipal Solid Waste", to be published in Resources, Conservation and Recycling, October issue 1995.
(35) Nedermark, R., Bang & Olufsen A/S, Denmark, personal communication.
(36) Sullivan, C.R., 1994, "Energy Use: The Most Important Environmental Impact of Electronic Equipment?", Proceedings of the 1994 IEEE International Symposium on Electronics & the Environment, San Francisco, pp. 261-266.
(37) The Energy Star Program, United States Environmental Protection Agency, 1993.
(38) Howard, B., 1994, "An Environmental Celebrity", PC Magazine, vol. 13, p. 105.
(39) Durham, T., 1993, New Scientist, October issue, pp. 30-33.
(40) Jacobsen, A., 1995, "Energy Optimization of Refrigeration Systems", Refrigeration Laboratory, The Technical University of Denmark (PhD-thesis to be published in the summer of 1995).
(41) Haller, H.O., Deutsche Thomson-Brandt GmbH, personal communication.
(42) "Electronic Scrap Ordinance", 1991, draft issued by the German Federal Department of Environment, Nature Conservation and Reactor Safety.
(43) Legarth, J.B., Alting, L., 1995, "Demands on Industry in Sustainable Use of Metal Resources", paper to be presented at the Symposium on Life Cycle Engineering Design, the 1995 ASME International Mechanical Engineering Congress and Exposition, San Francisco, November 1995.
(44) Jovane, F., Alting, L., Armillotta, A., Eversheim, W., Feldmann, K., Seliger, G., Roth, N., 1993, "A Key Issue in Product Life Cycle: Disassembly", Annals of the CIRP, vol. 42, No. 2, pp. 651-658.
(45) Seliger, G., Zussman, E., Kriwet, A., 1994, "Integration of Recycling Considerations into Product design - A System Approach", Integration: Information & Collaboration Models, Kulwer Academic Publisher, New York.
(46) Legarth, J.B., 1993, "New Strategies in the Disposal of Complex Products", paper presented at the biannual EDIP Meetings, February 1993, Denmark.
(47) Consoli, F., et. al., (Eds.), 1993, "Guidelines for Life-Cycle Assessment: A 'Code of Practice'", Society of Environmental Toxicology and Chemistry Workshop in Sesimbra, Portugal.
(48) Olesen, J., Hein, L., Jørgensen, J., Wenzel, H., 1993, "Structuring and Operationalization of EDIP Tools in Product Development Context", Restricted paper in Danish from the Institute for Product Development, Denmark.
(49) "LCA Software Buyers' Guide", 1994, Atlantic Consulting, London.
(50) Boustead, I., 1995, Boustead Consulting, West Grinstead, UK, Personal communication.
(51) Person, L., 1995, Chalmers Industriteknik, Göteborg, Sweden, Personal communication.
(52) Bensahel, J.-F., 1995, Ecobilan, Paris, France, Personal communication.
(53) Goedkoop, M., 1995, Pré Consulting, Amersfoort, The Netherlands, Personal communication.
(54) Virtanen, Y., 1995, VTT, Espoo, Finland, Personal communication.
(55) Steen, B., Ryding, S., 1992, "The EPS Enviro-Accounting Method: An Application of Environmental Accounting Principles for Evaluation and Valuation of Environmental Impact in Product Design", Swedish Environmental Research Institute, Sweden.
(56) "VDI-Richtlinie 2243: Konstruieren Recyclinggerechter Technischer Produkte", in German.
(57) Bullinger, H.-J., Bopp, R., 1994, "Methods and Tools to Support Design for Recycling", Proceedings of the CIRP 2. International Seminar on Life Cycle Engineering, Erlangen, Germany, pp. 106-127.
(58) Zussman, E., Kriwet, A., Seliger, G., 1994, "Disassembly-Orientated Assessment Methodology to Support Design for Recycling", Annals of the CIRP, vol. 43, No. 1.
(59) Hentscel, C., Seliger, G., Zussman, E., 1994, "Recycling Process Planning for Discarded Complex Products: A Predictive and reactive Approach", Proceedings of the CIRP 2. International Seminar on Life Cycle Engineering, Erlangen, Germany, pp. 195-209.
(60) Kriwet, A., Zussman, E., Seliger, G., 1994, "Systematic Integration of Design-for-Recycling into Product Design", International Journal of Production Economics.
(61) Pneuli, Y., Zussman, E., Kriwet, A., Seliger, G., 1994, "Evaluating Product End-of-Life Value and Improving it by Redesign", IIE Transactions on Design and Manufacturing.
(62) Krause, F.-L., 1995, Fraunhofer-Institut für Produktionsanlagen und Konstruktionstechnik (IPK), Berlin, Germany, Personal communication.
(63) Spath, D., Weule, H., 1994, "The Utilization of Hypermedia-Based Information Systems for Developing Recyclable Products and for Disassembly Planning", Annals of the CIRP, vol. 43, No. 1, pp. 153-156.
(64) Hartel, M., Spath, D., 1994, "Öko-Portfolio: Methode zur Beurteilung der Recyclingeignung Technischer Serienprodukte", VDI Berichte Nr. 1171, pp. 371-392, in German.
(65) Navin Chandra, D., 1993, "ReStar - A Design Tool for Environmental Recovery Analysis", Proceedings of the ICED '93, WDK 22, vol. 2., pp. 780-787.
(66) Ishii, K., 1994, "LASeR - Users Manual" Life Cycle Engineering Group at Ohio State (LEGOS), The Ohio State University, Columbus, Ohio, USA.
(67) Feldmann, K., Scheller, H., Meerkamm, H., Krause, D., 1994, "Design for Recyclability and Economic Planning of Disassembly - Based on the Recyclinggraph Tool", Proceedings of the CIRP 2. International Seminar on Life Cycle Engineering, Erlangen, Germany, pp. 76-90.
(68) Dieterle, A., 1994, Lehrstuhl für Werkzeugmaschinen und Betriebswissenschaft, TU Munich, Germany, Personal communication.
(69) Iwata, K., Kojima, F., Fukuda, Y., Matsumoto, K., 1994, "A Study of Manufacturing System Design Methodology in Consideration of the Facility Life Cycle", Proceedings of the CIRP 2. International Seminar on Life Cycle Engineering, Erlangen, Germany, pp. 154-167.
(70) Kojima, F., Iwata, K., Fukuda, Y., Matsumoto, K., Mitsuyuki, K., 1994, "Manufacturing System Design Simulator based on Facility Life Cycle Model", Advancement of Intelligent Production, pp. 81-86.
(71) Guinee, J.B., Udo de Haes, H.A., Huppes, G., 1993, "Quantitative Life Cycle Assessment of Products - 1:Goal

Definition and Inventory", J. Cleaner Prod., vol. 1, No. 1, pp.3-13.
(72) Guinee, J.B., Heijungs, R., Udo de Haes, H.A., Huppes, G., 1993, "Quantitative Life Cycle Assessment of Products - 2:Classification, Valuation and Improvement Analysis", J. Cleaner Prod., vol. 1, No. 2, pp. 81-91.
(73) N.N., 1995, Ricoh Family, No. 35, pp. 10-15.
(74) N.N., 1995, Ricoh Family, No. 31, pp. 4-6.
(75) Tipnis, V.A., 1991, "Product Life Cycle Economic Models - Towards a Comprehensive Framework for Evaluation of Environmental Impact and Competitive Advantage", Annals of the CIRP, vol. 40, No. 1, pp. 463-466.
(76) Tipnis, V.A., 1993, "Activity and Economic Modeling for Design for Sustainability", in Working Papers from 1st CIRP Seminar on Life Cycle Engineering, June 1993, Copenhagen.