Incorporating Environmental Issues in Product Design and Realization

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Abstract

In this paper, a number of options and issues are illustrated which companies and organizations seeking to incorporate environmental issues in product design and realization should consider. A brief overview and classification of a number of approaches for reducing the environmental impact is given, as well as their organizational impact. General characteristics, representative examples, and integration and information management issues of design tools supporting environmentally conscious product design are provided as well.

1 From Design for Manufacture to Design for the Life Cycle and Beyond

One can argue that the "good old days" where a product was being designed, manufactured and sold to the customer with little or no subsequent concern are over. In the seventies, with the emergence of life-cycle engineering and concurrent engineering in the United States, companies became more aware of the need to include serviceability and maintenance issues in their design processes. A formal definition for Concurrent Engineering is given in (Winner, et al., 1988), as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements." Although concurrent engineering seems to span the entire life-cycle of a product according to the preceding definition, its traditional focus has been on design, manufacturing, and maintenance.

Perhaps one of the most striking areas where companies now have to be concerned is with the environment. The concern regarding environmental impact stems from the fact that, whether we want it or not, all our products affect in some way our environment during their life-span. In Figure 1, a schematic representation of a system's life-cycle is given. Materials are mined from the earth, air and sea, processed into products, and distributed to consumers for usage, as represented by the flow from left to right in the top half of Figure 1.

Published in Industry and Environment, Special Issue on Product Design and the Environment, United Nations Environment Programme Industry and Environment (UNEP/IE), Vol. 20, No. 1-2 (double issue), 1997 Invited contribution.

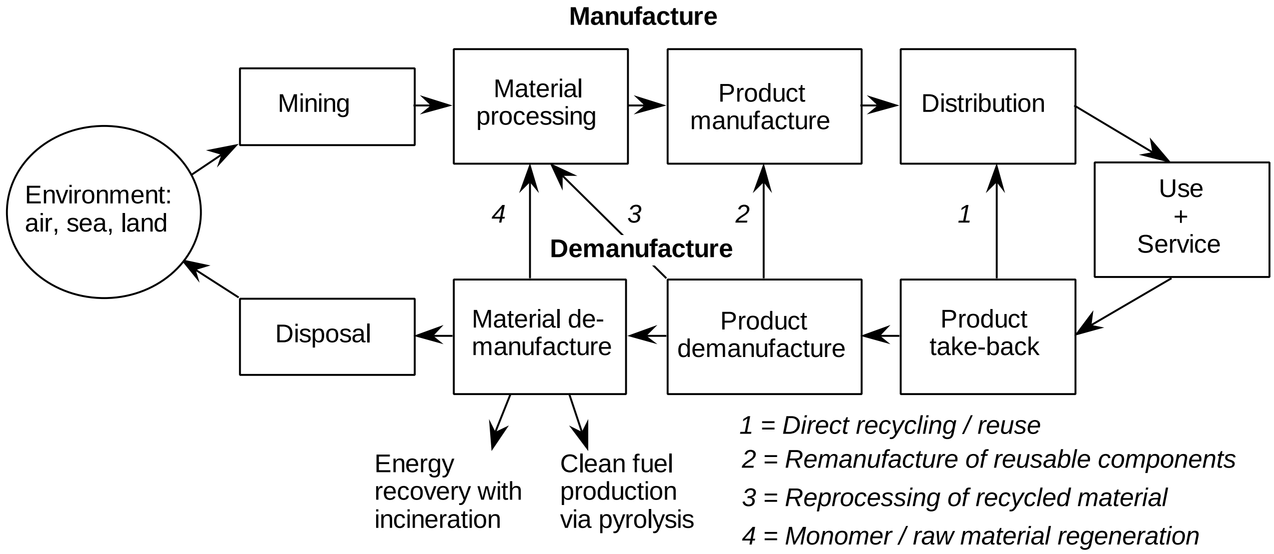

Figure 1 – A Generic Representation of a Product's Life-Cycle From Cradle to Grave and Reincarnation

In general, environmental impact comes from (excessive) consumption of natural resources and emissions of pollutants to air, water, and land. We are all familiar with the negative effects of air emissions. Recognition of its effects has led, among others, to the Clean Air Act and Corporate Average Fuel Economy legislation in the United States. However, recently the end-of life and disposal issues have received more attention. The emergence of product take-back legislation in Europe (e.g., the German Closed-Loop Economy Law) has forced manufacturers to think more and more about how to dispose appropriately of their products through recycling and reuse (as represented in the flow from right to left and up in the lower half of Figure 1) and to include product retirement issues such as recycling and disassembly as a real requirement in their design process. The term "demanufacture" is often used to characterize the process opposite to manufacturing necessary for recycling materials and products. Material demanufacture refers to the process of breaking down long polymers into smaller polymers which are then used for stock in new materials.

There are several motivating factors for a company or organization to become more environmentally responsible. Some of the most notable are:

- Legislation: For example, the US Clean Air Act has limited the use of a number of materials and (European) take-back legislation is driving Design for Recycling efforts.
- Customer demand: Awareness of environmental issues is increasing among customers. Some customers will even pay more for a product if it is green. Also, industrial customers (e.g., Original Equipment Manufacturers) do not want (future) environmental liability for a supplier's product.
- Eco-Labeling programs: How "green" is a product? Having an eco-label becomes a competitive advantage.
- ISO 14000: The ISO 14000 (environmental management standards) certification may become a crucial element in doing business, like ISO 9000 (quality management standards).

In addition, many have noted that "Design for the Environment" (DFE) makes good business sense and has many other positive effects. For example, the reduction of material diversity leads to less diverse inventory, volume purchasing, and the opportunity to focus on a reduced number of (core) manufacturing processes. Life extension practices place renewed emphasis on design for serviceability which typically pleases customers. Environmental concerns are also stimuli for finding new creative solutions and products. However, this does not imply that one can always expect a financial reward from becoming environmentally responsible.

Many companies and organizations have realized the need to become more environmentally responsible. However, many are struggling with the questions how to move towards becoming a more environmentally responsible company in general and how to include environmental issues in product design in particular. There is no unique solution, but in order to move towards integrating environmental issues in product design, a company should ask itself (at least) the following questions:

1. What are the organizational motivation and targets for integrating environmental issues?
2. What are the (current) organization capabilities and state?
3. What new practices, tools, and organizational structures are needed?
4. What is the best way of implementing the necessary changes?
5. What are mechanisms for continuous assessment, feedback, and improvement?

The purpose of this paper is to illustrate a number of options and issues that companies and organizations should consider in answering the preceding questions. Specifically, the focus is on the following:

- A number of approaches for reducing the environmental impact are discussed in order to provide a view of the current technology base.
- A number of organizational issues are highlighted to illustrate issues to be considered when identifying an organization's capabilities and state.
- General characteristics, representative examples, and integration and information management issues of design tools supporting environmentally conscious product design are discussed.

As will be shown, for a more comprehensive integration of environmental issues it is necessary to increase the scope of temporal and organizational concern of product design and realization.

2 APPROACHES FOR REDUCING THE ENVIRONMENTAL IMPACT OF PRODUCTS

In the last decade, the number and variety of persons and organizations working on addressing the environmental problems in engineering and industry has grown significantly. The general goal of environmentally conscious approaches to product design is the reduction of the negative environmental impact of a product throughout its life cycle. Several general approaches to reducing negative environmental impact can be identified (Coulter, et al., 1995). They can be distinguished by differences in scope of organizational and temporal concern, as shown in Figure 2. Ideally, one would like to move from the lower left corner (arguably the current state of practice) to the upper right corner of Figure 2 and achieve sustainable development. In Figure 2, rather than indicate years, the temporal concern gradations were based on life spans of products, people, and civilizations. The scale as shown is not linear but instead used to indicate important distinctions between the approaches. Within a product life cycle an additional set of distinctions were made, indicating manufacturing, use, and disposal as possible lengths of temporal concerns. It is recognized that a product life cycle could be as short as 1-2 years for consumer electronics or longer than 30 years for an airplane or ship, and that the application of a given approach might change accordingly. Similarly, the scale of environmental concerns was chosen to indicate distinctions. These gradations are fairly self-explanatory; although it is worth noting that "X products" refers to the negative environmental impact of a group of products, and that a scope equivalent to "One Manufacturer" would indicate concern about all the activities of a single manufacturing firm whereas "X Manufacturers" indicates activities among a group of manufacturers.

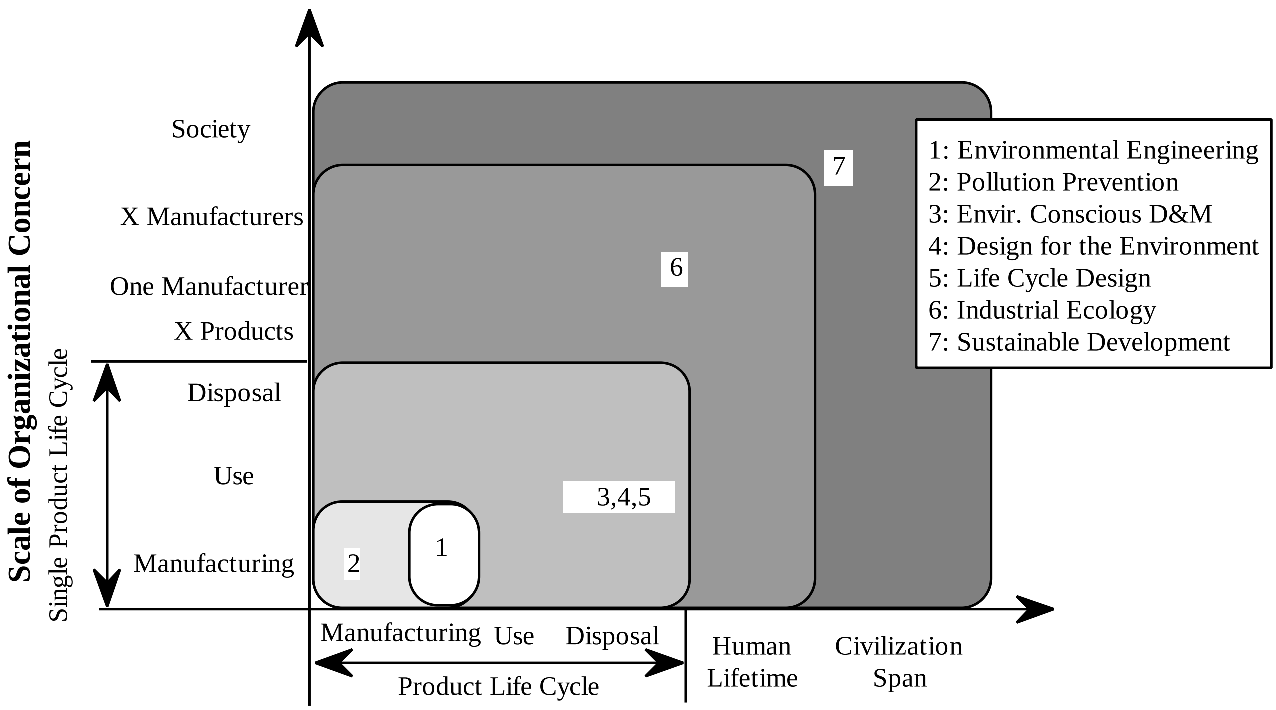

Figure 2 – Environmental and Temporal Scale of Environmental Impact Reduction Approaches

We note that three classes of approaches can be identified, namely,

- those which are applied *within* a single product life-cycle and focus on *specific* life-cycle stages,
- those that focus on a *complete* product life-cycle and cover *all* life-cycle stages, and
- those that go *beyond* single product life-cycles.

2.1 Approaches Focusing on Specific Product Life-Cycle Stages

Traditional environmental engineering is concerned with managing the fate, transport, and control of contaminants in water supplies and discharges, air emissions, and solid wastes. In the manufacturing context, the focus of environmental engineering effort is after pollutants have been generated, or at the "end of the pipe".

Practiced in industry, pollution prevention usually focuses on elimination of pollutants from existing products and process technologies (Freeman, et al., 1992, The National Advisory Council for Environmental Policy and Technology, 1993). Pollution prevention efforts are often mandated by legislation. For example, US regulations require pollution prevention programs for companies emitting hazardous substances. Pollution prevention efforts are broader than traditional environmental engineering efforts, as indicated in Figure 2.

With the exception of Design for Environment, environmentally oriented Design for X approaches (such as Design for Recycling, Design for Disassembly, etc.) are also focused on a specific aspect of a product's life-cycle. Although DFX approaches are well known and in many cases well excepted in product design, one danger of focusing too much on specific DFX approaches (or specific aspects of a product life-cycle in general) is that strong concentration on a single environmental aspect may negatively affect other aspects and render the product less environmental friendly as a whole. For example, the shift from thermosets towards better recyclable thermoplastics in car-design may be counter-effective in certain cases, because in order to compensate for the diminished strength of the thermoplastics, their mass has to be increased, leading to potentially higher emissions from the manufacture of the plastics and a heavier product needing more transportation energy, and (thus) an increase in the overall environmental impact of the product, even though recyclability is increased. This understanding has led to the development of approaches which focus on a complete product life-cycle.

2.2 Approaches Focusing on a Complete Product Life-Cycle

It is generally agreed that environmental considerations cover a product's entire life cycle and that a holistic, systems-based view provides the largest capability for reducing environmental impact of both products and associated processes (Congress, 1992, EPA, 1993). In Design for Environment (Ashley, 1993, Fiksel, 1996a, Navin-Chandra, 1991), Life-Cycle Design (Alting and Joergenson, 1993, EPA, 1993), Environmentally Conscious Design and Manufacturing (Baca, 1993, Owen, 1993), and Green Design (Congress, 1992), the scope of considerations, both in terms of time and the environment, is the life cycle of one product (see Figure 2 and also Figure 1). Environmental concerns include all phases of this life cycle, extending beyond the scope of pollution prevention to include the negative impact resulting from the use and disposal of this product. Similarly, the time scale considered is that of the product life cycle, from design and manufacturing through use and final disposal or recycling of the materials in the product. All these approaches have similar goals and encourage a holistic product view. However, it has already been recognized by many that this may not be enough. For example, modern manufacturers often rely on multiple suppliers, have multiple product lines, multiple facilities, often in multiple countries.

2.3 Approaches Going Beyond Single Product Life-Cycles

In contrast to the preceding approaches, industrial ecology is not limited to a single product life cycle, but considers the interactions of several product life cycles (of possibly different lengths) over a larger time scale. Industrial ecology provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems analogous to the metabolism (use and transformation) of materials and energy in biological ecosystems (Ayres, 1994, Frosch and Gallopoulos, 1989, Graedel and Allenby, 1995). In industrial ecology, companies, organizations and communities work together to minimize environmental impact and use each others waste in an intelligent manner for creating new products. For example, a carpet industry's production waste can be used by car companies to make sound-deadening materials. On the other hand, polyurethane seat foam taken from recycled cars can be further processed into carpet underlayer. In this example, an carpet manufacturer, car company, and seat recycling company have a symbiotic relationship like found in a biological ecosystems and formed what is termed an industrial ecosystem. Moving from towards industrial ecology generally requires cooperation between several industries (a vertical move in Figure 2).

The broadest approach, in terms of the scope of environmental and temporal concerns, is sustainable development and technology. The United Nations' World Commission on Environment and Development in their report *Our Common Future*, defines sustainable development as "development that meets the needs of the present generation without compromising the needs of future generations." Sustainable development has also been adopted by the Clinton Administration in the US (Clinton and Gore, 1995, Schaefer, et al., 1994). Sustainable development is also the least well-defined approach in terms of tools and methods. It is generally agreed that sustainable development requires at least pollution prevention, consideration of life-cycle consequences of production, and an approach that imitates natural or biological processes. The Natural Step, a Swedish non-profit organization, has postulated a number of system conditions for sustainability based on the Laws of Thermodynamics.

In general, environmental impact reduction approaches extending beyond a single life cycle (industrial ecology, sustainable development) have been implemented at more of a management level, with general strategies proposed but little indication of implementation details. E.g., it is difficult to find an example of industrial ecology which illustrates the entire scope of this approach; implementation on a multi product life-cycle scale does not appear to have been done. Most work described as applications of industrial ecology, e.g. (Klimisch, 1994, Sekutowski, 1994) instead indicate the use of this general approach at the level of a single product life cycle. True implementation of the approach would require integration of the product life cycles for multiple products, as indicated in (Richards and Fullerton, 1994).

With respect to the current organizational capabilities and state of companies, most larger companies in the US will have pollution prevention practices in place and are moving towards approaches such as Life-Cycle Design in Figure 2. Some companies have started to embrace the notion of sustainable development (Hart, 1997, Magretta, 1997). Many smaller companies are still struggling in the lower left corner of Figure 2.

As an aside, we have found the map in Figure 2 to be an extremely effective way of communicating the differences in approaches and overall goal for the following reasons:

- The map clearly indicates the key differences between different approaches, namely, organizational and temporal scale.
- The map also indicates that broader approaches still include principles from more focused approaches. For example, pollution prevention is and should be part of, e.g., Design for Environment.
- As a rule of thumb, the darker the region in Figure 2, the less established the approach is.
- The map also provides a means for assessing the current state of an organization and what the overall target and roadmap are. For example, a company with a well established pollution prevention program and interested in moving towards sustainable development should first become well versed in environmentally conscious design and industrial ecology prior to reaching sustainable development.

3 Organizational Aspects of Integrating Environmental Issues

A company or organization seeking to integrate environmental issues in product design needs to consider its organizational capabilities and structure. Furthermore, in many cases, the company or organization relies on others to do the product design, or at least part of it. In such cases, outreach to other companies and providing leadership or stewardship becomes on integral part of integrating environmental issues into product design.

Generally speaking, modern product design is always trying to get a better and cheaper product out in less time. Product design is typically multi-disciplinary and multi-leveled. In Figure 3, different levels of design concern and integration are shown. At the lowest level, the various parameters (e.g., the size of a crank shaft) are determined, whereas at the subsystem level, components and/parts are integrated into subsystems (e.g., into an internal combustion engine). At the product level various subsystems are integrated into complete products which are either a) sold by a supplier to an Original Equipment Manufacturer for inclusion in their products (e.g., an engine and transmission are combined to form a powertrain to be sold to a car manufacturer) or b) directly to a customer (e.g., a car from a automobile manufacturer). Clearly, to achieve the technically, economically, and ecologically best product in the least time, communication between the various levels of product realization in Figure 3 is a must. For example, if an OEM decides to eliminate cadmium and zinc coatings, it will affect their suppliers. Many large OEMs, e.g. in the electronics and automotive industries, have very close working relationships and share design information with their suppliers in order to decrease lead-time and cost, and increase quality. However, many smaller companies do not have their own design department (Hemel and Keldmann, 1996). Hence, they will have to rely on others, say, engineering consulting firms.

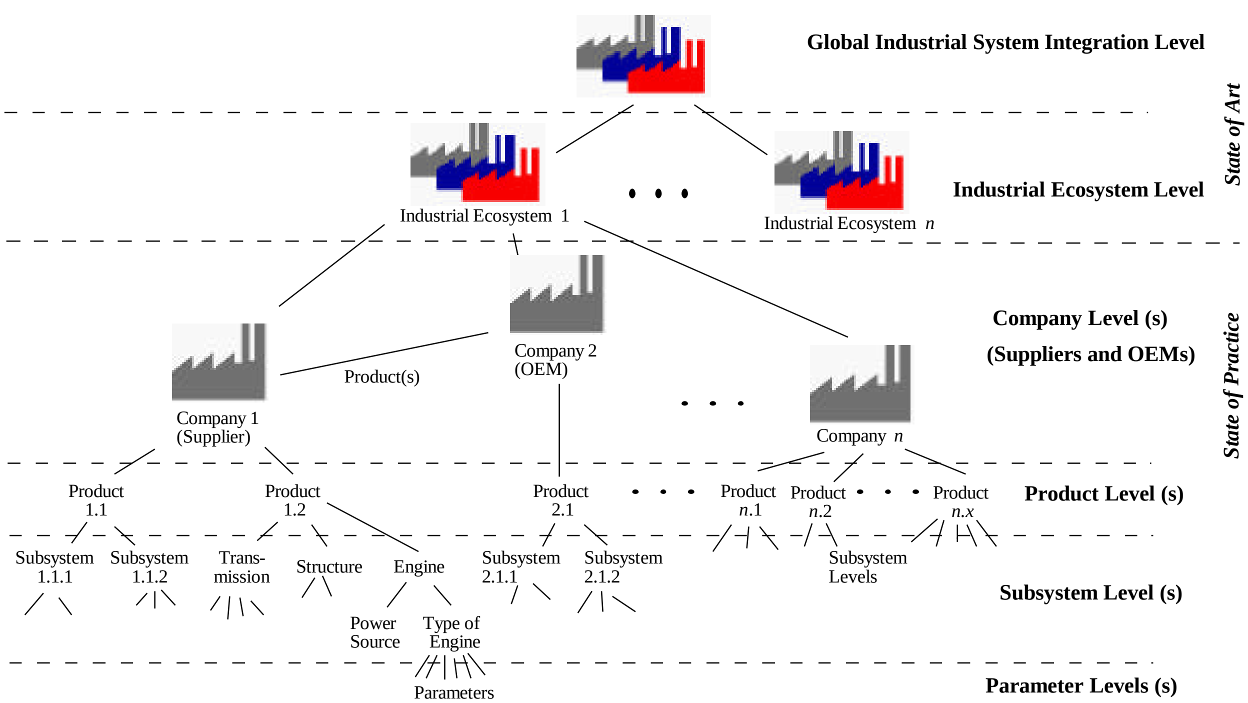

Figure 3 – Increasing Levels of Organizational Design Concern

The next levels are less well-established. At the company level(s), design information is shared bilateral between suppliers and OEMs, but material in the form of products flow only from suppliers to OEMs. The industrial ecosystem level is characterized by the fact that material flows are shared between companies and a biological metabolism of waste is mimicked. Perhaps the highest level of industrial organization is a global industrial system integration where several industrial ecosystems cooperate at a global level. Needless to say that we are far from achieving the latter level of integration, nor do we know whether it is even desirable. However, we do see a trend in many places towards industrial ecosystems. The Kalundborg industrial ecosystem in Denmark is a well cited example. One advantage of forming an industrial ecosystem is that the focus changes from merely minimizing waste from a specific process or facility to minimizing waste produced by the larger system as a whole. Arguably, by cooperation in an industrial ecosystems, the participants will achieve a greater waste reduction and/or material use efficiency than as isolated elements. In fact, in an industrial ecosystem, one element of the system may actually produce more waste than before, as long as the other partners are capable of absorbing it and the overall waste output of the system is reduced.

As an example of close cooperation with life-cycle partners, consider the automotive industry. In Figure 4, an overview of a car's life-cycle is given with corresponding interest groups and (basic) material flow. This can be thought of as an industrial ecosystem, albeit that nobody would currently refer to it in that fashion. The automotive industry is a classical example of an OEM with a large supplier base. More and more automotive component design are outsourced to suppliers. We can see a definite movement towards increased sharing of information and even material. For example, car manufacturers now encourage suppliers to take back their products for recycling.

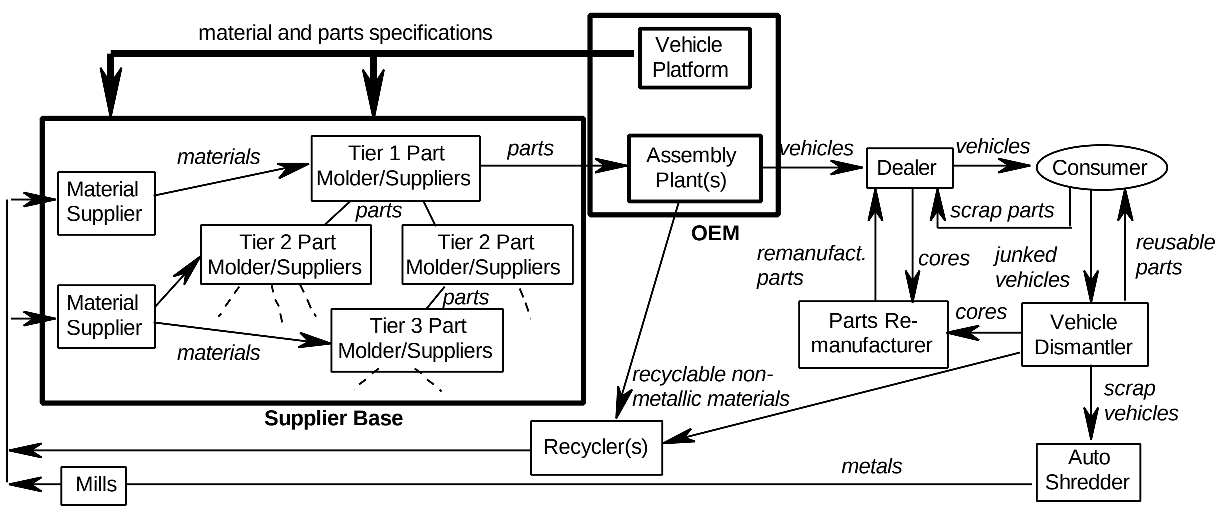

Figure 4 – Vehicle Life-Cycle and Industrial Interest Groups

Figure 4 exemplifies the amount of interactions that product designers need to consider when pursuing environmentally conscious design. Indeed, some automobile companies are very active in educating their design engineers about the effects of their design on pollution prevention and end-of-life concerns. Part of this knowledge stems from close collaboration with dismantlers, recyclers, and remanufacturers. Clearly, an important issue to consider is to what extent will suppliers and product realization partners have to change if a company decides to move towards sustainable development and to integrate environmental issues in its product design and realization practices.

4 TOOLS SUPPORTING ENVIRONMENTALLY CONSCIOUS DESIGN

4.1 General Issues and Selection Criteria

The number of tools for supporting specific aspects of environmentally conscious design, life-cycle design, DFE have increased significantly. For example, a decade ago, there were no tools for assessing the disassemblablity and/or recyclability of a product whereas currently there is enough variety for benchmarking (Boothroyd and Alting, 1992, Hrinyak, et al., 1996). Any company or organization seeking to integrate environmental issues in product design and realization should ask itself the following questions:

1. What new tools should we provide designers to aid them in coping with this increased emphasis on designing for the life-cycle?
2. How can these tools best be integrated into the existing and well-established design systems, tools, and practices?
3. How do we minimize overlap and increase efficiency in information gathering and management?

The goal of introducing new tools should be to provide efficient and effective decision support in environmentally conscious design where efficiency is a measure of swiftness and effectiveness, on the other hand, is a measure of completeness and correctness. In order to meet this goal, metrics, associated models, and resulting decision support tools should ideally have the following seven characteristics (Hrinyak, et al., 1996):

- *Simple* - they should be easy to use;
- *Easily Obtainable* - at a reasonable cost;
- *Precisely Definable* - it is clear as to how they can be evaluated;
- *Objective* - two or more qualified observers should arrive at the same result;
- *Valid* – they should measure, indicate, or predict *correctly* what they are intended to measure, indicate, or predict;
- *Robust* – relatively insensitive to changes in the domain of application;
- *Enhancement of Understanding and Prediction* – good metrics, models and decision support tools should foster insight and assist in predicting process and product parameters.

The tools and techniques for supporting integration of environmental issues in product design can also be classified along the time and concern scales in Figure 2. In keeping with the different approaches mapped in Figure 2, in general, there is a need for

- tools which assess/analyze different aspects of a product's life-cycle (such as recyclability and remanufacturability assessments),
- tools which allow an assessment/analysis of the entire product's life-cycle (e.g., Life-Cycle Analyses and Costing) are needed,
- tools which facilitate trade-off analyses in pursuing various life-cycle aspects, i.e., decision support tools which include technical, economical, quality, and environmental concerns.

It is important to keep the organizational aspects as well as (potential) time-dependency of tools in mind. Designers at the part level (see Figure 3) have different requirements for a tool than designers/managers at the company level who interact with suppliers and sign-off on whole products. The former need very specific tools whereas the latter needs broader, integrative tools. Furthermore, some tools can only be applied if the product's structure, materials, and manufacturing processes are defined at which stage it typically is very difficult to alter a design significantly if a reduction in environmental impact is needed. The type of product and business will also drive the need for tools. For example, a carpet manufacturer will not need a disassemblability assessment tool like a consumer electronic manufacturer. However, both will arguably need a Life-Cycle Analysis tool.

4.2 Design Guidelines and Checklists

Design guidelines are among the most basic tools in design and the introduction of appropriate design guidelines is one of the easiest way in introducing environmental issues in design. A number of design guidelines ranging from a focus on specific aspects of a product's life cycle (e.g., "reduce the number of materials used to facilitate more efficient recycling") to sustainable development (e.g., "reduce the use of non-renewable energy sources") have been developed in recent years. It would go beyond the scope of this paper to list them all. Representative examples can be found in (Berko-Boateng, et al., 1993, Brezet et. al., 1994, Congress, 1992, EPA, 1993, Fiksel, 1996c, VDI, 1993). Guidelines with respect to life-cycle strategies are given in Figure 5 as well. Guidelines can be augmented with checklists in which a designer marks whether he or she has considered the corresponding guideline. Combined with a short course or dedicated education session, guidelines and checklists provide an effective means for exposing designers to environmental issues and ways to reduce the environmental impact of their products, especially when they are in line with enhancing other life-cycle aspects. For example, the standardization and reduction of number of fasteners used in a product not only facilitates recycling and remanufacture but also manufacturability - a key concern of many designers and companies. However, the greatest drawback of design guidelines is their qualitative nature which hinders the assessment of trade-offs in particular.

4.3 Quantitative Design Assessments

Quantitative metrics are needed to assess the progress and provide means for continuous improvement and feedback when integrating environmental issues in design. A variety of metrics have been proposed to allow comparison of designs, with most being based on some variant of life-cycle assessment (LCA). A nice survey of LCA applications in European firms is given in (Berkhout, 1995). In many cases, a full assessment of the entire environmental costs is not feasible given the work that would be required and the uncertainty in forecasting the changes in the economy and technology over the life of most products (Congress, 1992). Instead, the designers of these metrics attempt to achieve a balance between reducing the level of detail required and increasing the accuracy of the metric. E.g., in (Graedel, et al., 1995), an LCA matrix approach is introduced which is designed for use in the early stages of design for complex products such as automobiles. The level of detail and the accuracy of the result are fairly low, but may be appropriate for the early stages of design. This can be compared to the work described in (Navin-Chandra, 1993) which requires significantly more detailed information while returning a more accurate result. The trade-off in this detail is evident in the examples of application; Graedel's approach is applied to automobiles, while Navin-Chandra's tool is demonstrated on a coffee maker. A variety of metrics and approaches for the use of these metrics can be found in the literature which span different levels of detail and accuracy, e.g., (Bor and Kant, 1993, Coogan, 1993, Coulter, et al., 1996, Fiksel, 1993, Fiksel, 1996b, Keoleian and Menerey, 1994, Portney, 1993, Shapiro, 1993, Sullivan and Young, 1995, Tolle, et al., 1994).

In many cases, assessment tools proposed for use in engineering design are based on Design for X methodologies. Most mechanical product designers are familiar with assemblability assessments, e.g., using Boothroyd-Dewhurst's method (Boothroyd and Dewhurst, 1991, Leaney, 1996). Methods for assessing other life-cycle aspects, e.g., serviceability (Dewhurst and Abbatiello, 1996) and remanufacturability (Amezquita, et al., 1995, VDI, 1993) also exist, but are less well institutionalized. In general, these types of assessments fall under the realm of Design for X approaches (see also Section 2). A good overview of DFX can be found in (Huang, 1996).

In some cases, industry has taken the lead in defining assessment tools and metrics. For example, the North American automakers have developed a method for calculating vehicle recyclability as a percentage of weight based on two ratings for each component (Coulter, et al., 1996):

- a *recyclability rating*, ranging from 1 (best) to 6 (worst), and
- a *material separation rating*, ranging from 1 (best) to 5 (worst).

It is likely that this assessment method will become a standard for the North-American automotive industry.

4.4 Relative versus Absolute Design Assessments

Even though the number as well as the maturity of different life-cycle indices and indicators presented in the literature is rapidly increasing, they still suffer from the fact that a) lot of data is missing and b) that questionable weights and criteria are used because non-comparable units of measurements are used, thus leaving a lot of unanswered questions and room for political debate. An excellent critique can be found in (Ayres, 1995). Additionally, the perceptions about environmental impact differs between countries. In Europe, a substantial amount of good research and development is done on Life Cycle Analyses/Assessment tools. However, the material databases developed for these analyses are not directly transferable from Europe to the US because of differences between European and US legislation and toxicity classifications. Nevertheless, many are still very suitable for use in design if one seeks to assess ***relative*** product improvements rather than *absolute* environmental impact.

As a nice representative example of a relative improvement assessment, consider the recently developed LiDS (Lifecycle Design Strategies) Wheel in Figure 5 (Hemel and Keldmann, 1996). The LiDS Wheel is part of the Dutch Promise Manual (Brezet et. al., 1994) of which an English translation is planned for publication by UNEP/IE. The wheel asks companies to assess their current state with respect to eight life-cycle strategies. Note that design guidelines are incorporated as part of the eight strategies in the wheel. Companies can map their current efforts in the spider diagram which highlights where their weak areas are. Once improvements have been made (or planned), a new assessment can be made and overlayed on top of the previous one, thus showing relative improvements. Note that no scales are defined. Also, there is no exact correlation between efforts and actual environmental impact. Yet, the wheel visually conveys a company's relative effort and impact.

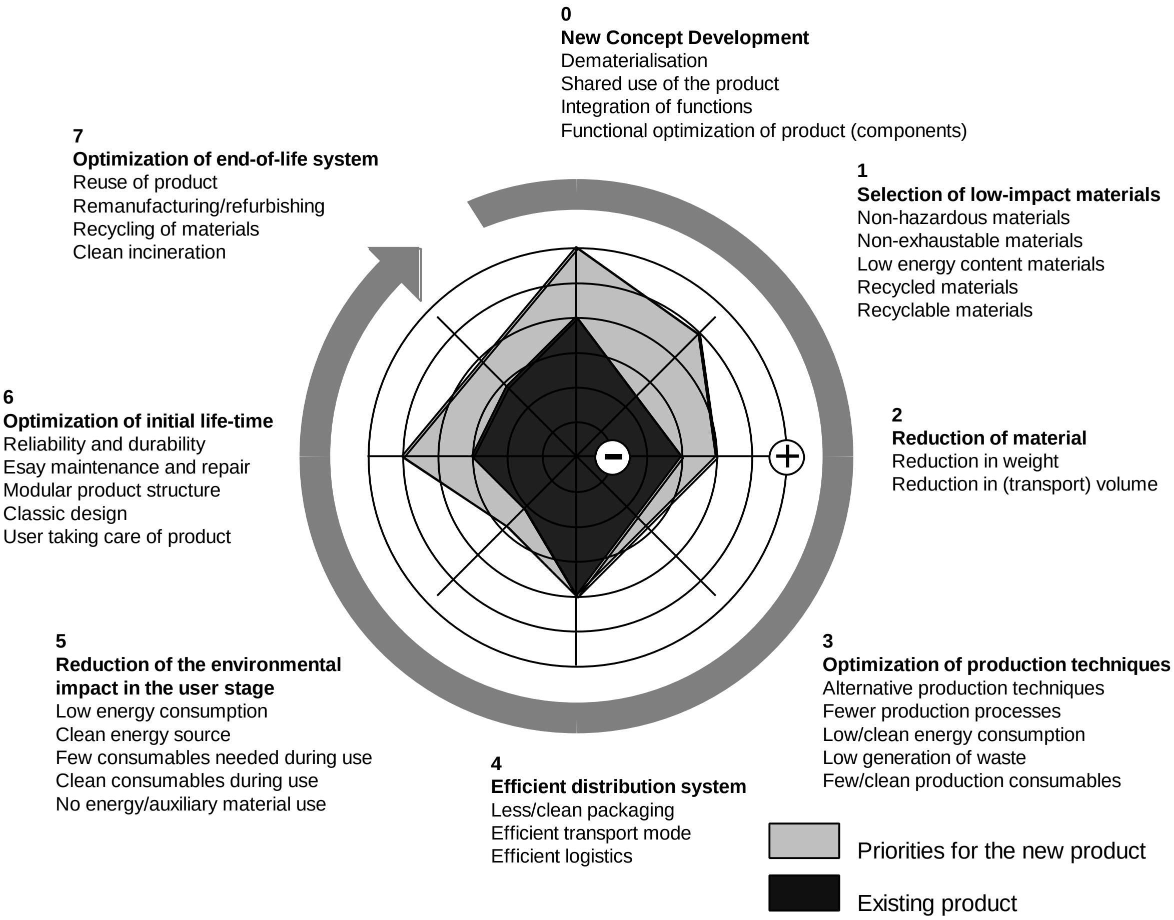

Figure 5 – LiDS Wheel (Brezet et. al., 1994, Hemel and Keldmann, 1996)

Another example of a relatively simple tool for relative comparison is the matrix based life-cycle assessment approach described in (Graedel, et al., 1995). Such simple assessment tools relieve small and medium sized companies from spending resources on excessive education and/or high tech (computer) equipment. For example, the Promise manual and LiDS wheel have been explicitly targeted to small and medium sized companies. Clearly, the level of sophistication needed is a function of organizational scope and capabilities.

4.5 Decision Support Tools

Tools for decision support and trade-off analyses are less well established. Many developments in this domain are concerned with the trade-off between environmental impact and financial costs/profits (Barbera and McConnell, 1990, Todd, 1994). When it comes to assigning costs to life-cycle and ecological issues, Activity-Based Costing (ABC) is gaining ground rapidly on conventional costing systems (Bras and Emblemsvåg, 1996, Brooks, et al., 1993, Cooper, 1990, Keoleian and Menerey, 1994). However, issues like the costs of using non-renewable versus renewable resources are still unresolved. Design for assembly versus disassembly is another area where trade-off issues are being investigated, primarily due to the importance of assemblability considerations in product realization.

When it comes to tools extending beyond a product life cycle and a single manufacturer, i.e., tools for supporting industrial ecology and sustainable development, few developments (with the exception of qualitative design guidelines) have been made so far. Decision support tools for industrial ecology will have to allow for the modeling and simulation of material input and output flows between various companies in order to assess the overall environmental impact of industrial ecosystems and the exploration of different scenarios for the formation and working of industrial ecosystems (Bras, 1996).

4.6 Integration into Design Practice and Information Management

Once the necessary tools have been defined, the integration of environmental issues and tools in a the existing operating procedures of a product design group is still a significant challenge. Primarily because the designers are often asked to do more in the same amount of time. Many case studies and experiences regarding introducing environmental concerns in a corporation can be found in the literature, e.g., (Fiksel, 1996a). A number of issues with respect to integrating industrial ecology are listed in (Richards, et al., 1994). In (Brezet et. al., 1994), an eco-design approach and supporting tools focused on the design practice of small and medium sized companies is documented. Clearly, one should always consider the following:

- Who is supposed to use the tools, i.e., who is the audience?
- Why would they use them, i.e., what is their incentive?

With respect to the users, one should carefully plan by whom and where in the design process the tools should be used. For example, it does not make sense to have designers who work primarily with sheet metal do a recyclability improvement exercise because sheet metal is already easily recyclable. Also, the introduction of highly sophisticated computer tools (e.g., a virtual product disassembly tool) does not make sense for a company without a well-established computer infrastructure.

With respect to incentives, introducing new design guidelines and/or engineering standards dealing with environmental issues may not result in any increased effort unless a sign-off and/or check is required, thus sending a message to designers that they must comply with the new design requirements. For example, car manufacturers have introduced engineering guidelines for reducing substances of concern and increasing vehicle recyclability (e.g., General Motors 1000-M and 502-M standards, and Chryslers' CS 9003 standard) and require documentation from design engineers and suppliers, thus emphasizing the importance of compliance and providing an incentive. On the other hand, these companies also provide education and support services to designers and suppliers by specialized groups. And some OEMs reward suppliers financially for environmental excellence.

It should be noted that the simpler the assessment method, the easier it will be accepted by designers in their current day to day activities. The author was once told by a high level industry representative that "as long as it fits on one sheet of paper, designers will read and do it". Quite a challenge, but it does lower the acceptance threshold significantly. Other industry representatives are also starting to question how much more they can burden their design teams to do more in the same amount of time.

A key concern, namely, in introducing new tools into a design process is the gathering, management, and leveraging of information required for environmental assessments. Although the number of tools available is rapidly increasing, many are stand-alone tools and very few allow sharing of information. A designer is often forced to reenter the same data in different software packages, and not only for environmental assessments. Any company thinking about introducing new tools for environmentally conscious design should seriously consider the human and information factors involved. The objective should be to minimize the amount of information gathering and management as much as possible in order to increase the efficiency of designers while at the same time increasing their scope of concern and effectiveness. One should, therefore, always try to integrate new tools into existing and accepted design systems. However, this may lead to the insight that research and development in new systems is appropriate. For example, one can argue that conventional CAD systems are not the most efficient support for a more integrated approach to life-cycle design due to their heavy focus on geometric information management (Rosen, et al., 1996). New computer-based design systems will have to be developed to fully support environmentally conscious design. As a representative example of such development of new systems, consider the next generation computer-based design system architecture presented in Figure 6 which is under development in our Georgia Tech System Realization Laboratory. Its purpose is to support Design for the Life Cycle. As can be seen in Figure 6, it contains both product and process design modules. Included in the product design module are synthesis, selection, and evaluation modules. The objective is to increase the efficiency and effectiveness of designer among others by reducing the duplication of information entry and by leveraging information for a greater variety of assessments. The system in Figure 6 is representative of the types of design systems that are needed to support integration of environmental issues in modern product design.

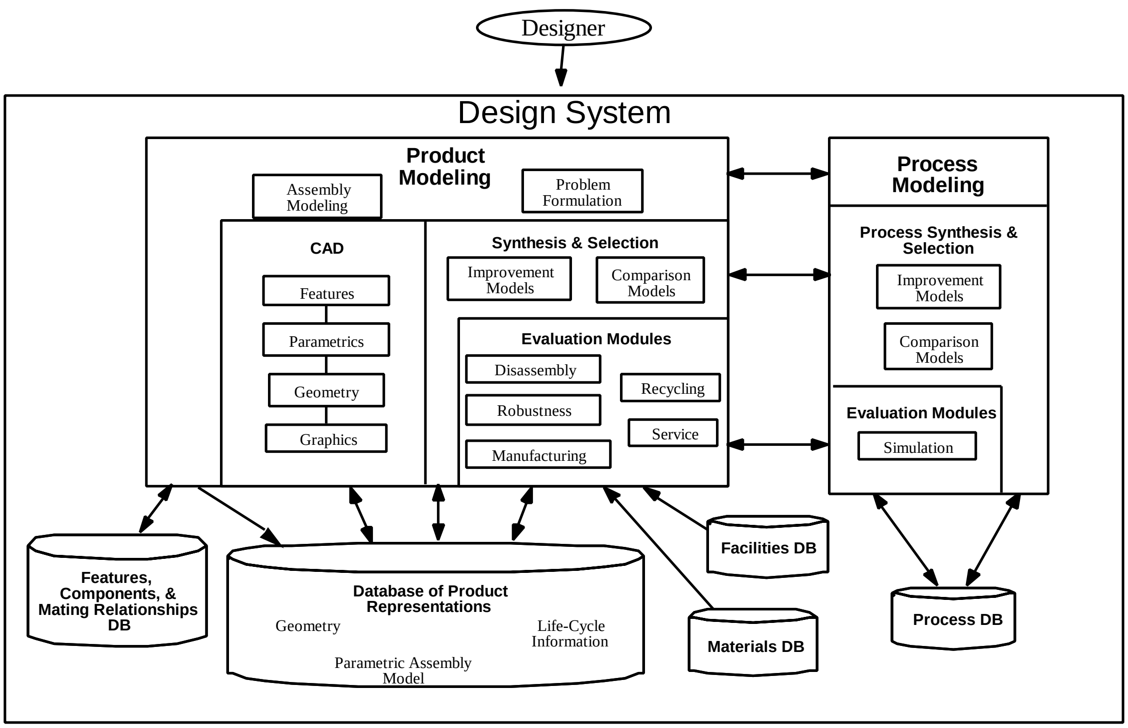

Figure 6 – Computer-Based Design for the Life-Cycle System Architecture

5 EDUCATION – A NECESSARY PREREQUISITE TO ALL OF THE ABOVE

Technology cannot solve all problems. Perhaps the most important issue in moving towards integrating environmental issues in product design is education. For example, in the US, a large number of graduating mechanical engineers (still) do not know that Toxic Release Inventories and pollution prevention programs are required by law for generators of hazardous materials, and that failure to comply may result in criminal prosecution. Many European technical universities nowadays require their engineering students to take a class on Environmentally Conscious Design and Manufacture. According to (Congress, 1992), although a large number of US universities claim to work on environmental issues, only a few have formal courses in place. This is changing rapidly and the opportunity for creating an impact through education is enormous. As an example, consider the author's institution, the Georgia Institute of Technology which has the largest College of Engineering in the US. Its School of Mechanical Engineering alone graduates yearly two percent of all mechanical engineers in the US. Five years ago, with the exception of civil and environmental engineering, no engineering student was exposed to environmental issues in his or her discipline. Now, lectures on environmental issues are integrated in various engineering design and manufacturing classes and students can also take specialized classes in Environmentally Conscious Design and Manufacture as well as Sustainable Development (Bras, et al., 1995). Large companies have also stepped up in educating their workforce and suppliers. For example, GM, Ford, and Chrysler all provide design for recycling and design for environment training courses for their employees and suppliers.

Related to education is the dissemination of information. Much information regarding environmental issues is available from, say, chemical engineering, but where would a mechanical engineer working in a small company retrieve relevant information? Interestingly, the rapid development of the internet has opened new and faster avenues for information dissemination. Many organizations publish relevant information for free on the World Wide Web, ranging from Material Safety Data Sheets to actual case studies and tool demos.

6 CLOSURE

In this paper, a number of options and issues that companies and organizations should consider when pursuing integration of environmental issues in product design and realization. Clearly, a wide variety of approaches for reducing the environmental impact exists (see Section 2), as well as supporting tools (see Section 4). It is imperative that a company recognizes its current state and capabilities, as well as its motivation and target level for integrating environmental issues in product design and realization. Furthermore, a unilateral decision may have deep consequences in today's highly integrated product realization practices (see Section 3). Nevertheless, in the US the following trends can be seen in industry:

- On the positive side, large US companies with global markets are closely paying attention to progressive European (and other) initiatives and legislation. In particular, the car companies (GM, Ford, and Chrysler), the electronic companies (e.g., those organized in the Microelectronics and Computer Technology Corporation - MCC), and large world-wide chemical companies and material suppliers (e.g., those organized in the American Plastic Council) are active and even extremely pro-active in some cases.
- On the negative side, small to medium size companies with domestic markets worry often only about satisfying local, state, and federal (EPA) regulations (if at all). Many small companies and/or Small Quantity Generators (i.e., those with less than a 1000 kilograms of hazardous

waste per month) have no clue about pollution prevention, let alone about DFE, industrial ecology, or even sustainable development.

With respect to small and medium sized companies, however, we are seeing a domino effect due to the fact that large Original Equipment Manufacturers are starting to force their first tier suppliers to comply with their proactive measures and foreign mandates as well. These suppliers are starting to pressure their suppliers, etc. In the near future, ISO 14000 may cause an even deeper ripple effect, augmented by increased awareness through education.

It is the author's experience that, invariably, everybody buys into the philosophy of environmentally conscious design, industrial ecology, and sustainable development. The challenge lies in the seamless implementation in existing and new practices. Many corporations, designers, and engineers agree that the issue is not *whether* they should become environmentally responsible in product design and realization, but *when* and *how*.

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