TEKES – Uudistuva teollisuus -aktivointihanke

Competitive and sustainable production systems and networks
(KEstävän KEhityksen kilpailukykyinen ekotuotanto KEKE)

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WP 6: Product and production systems life cycle and interaction

Table of Contents

Introduction

This work package focused on product life cycle and production system lifecycle. The aim was to describe these life cycles and then to consider the integration of product and production system life cycles. These aim at improving sustainability of products and production systems. The main focus was on product life cycle, especially product upgrading and post-use phases, e.g. reusing, remanufacturing and recycling.

Background

Growing environmental concerns, coupled with public pressure and stricter regulations are fundamentally impacting the manner in which companies design and launch new products across the world (Choi et al., 2008). Product design is one of the most important sectors influencing global sustainability, as almost all products consumed by people are outputs of the product development process. In particular, early design decisions can have significant impacts on sustainability. These decisions not only relate to material and manufacturing choices but have a far-reaching effect on products’ entire life cycles, including transportation, distribution, and end-of-life logistics. Lack of information models, semantic interoperability, methods to influence eco-design thinking in early design stages, measurement science and uncertainty models within eco-decisions, as well as the ability to balance business decisions and eco-design methodology are serious impediments to realizing sustainable products and services (Ramani et. al, 2010). It has been well observed that eco-efficiency, in general, has become a strong delighter to consumers. Therefore, integrating downstream life cycle data into industrially relevant design tools will be a key enabler to gain a significant competitive advantage for market share.

In the last three decades or so, lifecycle engineering has gained considerable traction and has shifted overall business strategies away from “concurrent engineering”, traditionally focusing on design manufacturing and maintenance to a more holistic approach which considers additional product-related phases preceding design and following maintenance. Professor Bert Bras of the George W. Woodruff School of Mechanical Engineering at Georgia institute of Technology states 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...[and] the most striking areas where companies now have to be concerned is with the environment” (Bras, 1997). This fundamental paradigm shift has made both modeling a product’s lifecycle stages and understanding the interactions between these product phases imperative for sustainable corporate growth.

Description and model of product life cycle

In general, the product life cycle can be described from a cradle to grave perspective. Figure 1 illustrates a system's lifecycle highlighting materials, which are mined from the environment, processed into products, distributed to users, and ultimately participate in various end-of-life pathways specific to the material makeup of the product. This approach has been well-accepted since the late 1990s. From this perspective, the product life cycle can be generally divided into the following stages (USEPA 2003):

- cradle to entry gate (raw material extraction and refining);
- entry gate to exit gate (product manufacture and distribution); and
- exit gate-to-grave (product use, recycling and disposal).

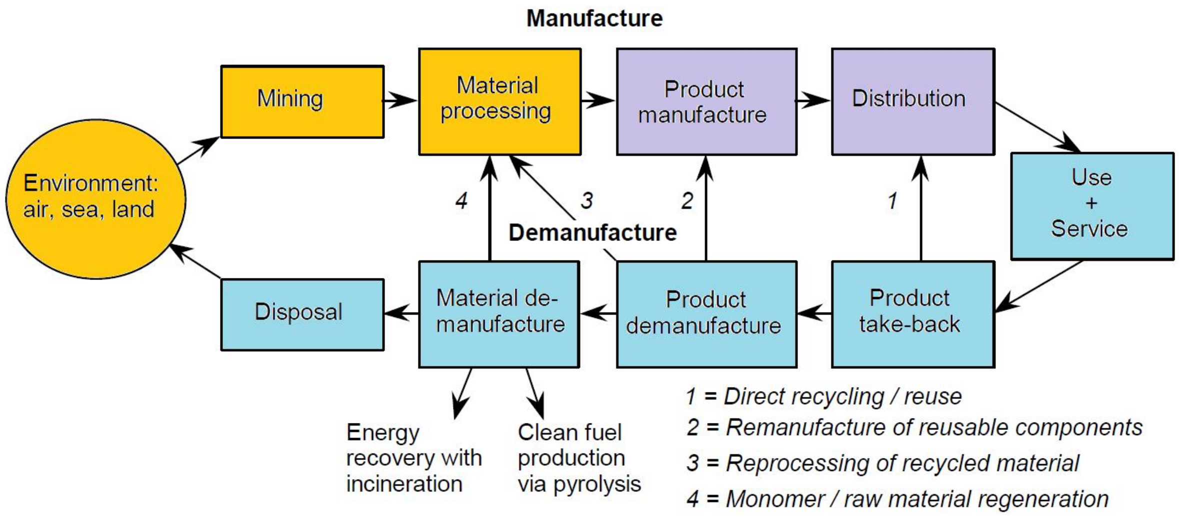

Figure 1: A Genetic Representation of a Product's Life-Cycle from Cradle to Grave and Reincarnation, adapted from (Bras, 1997). Cradle to entry gate, entry gate to exit gate, and exit gate to grave are represented by the colors orange, purple and blue, respectively.

The 6R Concept

Another way to envision the lifecycle is from a cradle to cradle approach, which is an attempt to shift from the traditional paradigm of pushing used materials back to the environment and instead reprocessing used resources from a product's lifecycle to contribute to another. This closed-loop product life-cycle view is illustrated in Figure 3. This methodology enables perpetual material flow, applying a 6R approach (i.e. the traditional, *reduce, reuse,* and *recycle,* along with the modern, *recover, redesign,* and *remanufacture*).

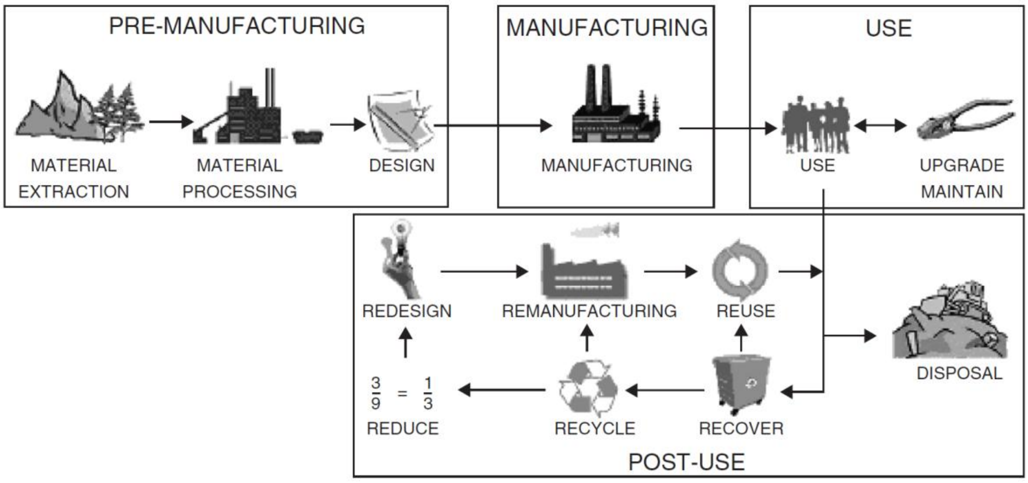

Figure 2: The closed-loop product life-cycle system showing the 6Rs for perpetual material flow (Jaafar et al., 2007)

To enable the benefits of the oversimplified 6R paradigm, it is necessary to define the associated terms and discuss methods for ultimate realization. *Reduce* refers to activities required to "simplify" the current design of the product in order enable additional postuse activities. Potentially incurring the least environmental burden and effective economical costs of all end-of-life activities is the *reuse* option due to its limited necessities for reprocessing. *Recycling* refers to re-entering used materials into the manufacturing stage. This can be done by a number of operations depending on the specific product architecture in question (i.e. smelting, shredding, separating, etc.). Recycling offers an environmentally efficient alternative to virgin materials. *Recover* represents the product's takeback logistics (transportation, disassembly, dismantling). *Redesign*, though seemingly obvious, is a significant step to enable any end-of-life pathway. *Redesign* works in close conjunction with *reduce* in that it involves redesigning the product in view of simplifying future postuse processes. *Remanufacture* refers to the subsequent manufacturing steps required to implement the redesigned product back into reuse pathways (Jaafar et al., 2007).

Though similar, this rationale is fundamentally different than Dr. Bras's depiction from Figure 1. The concept of redesigning recover, recycled and reduced materials from one product (as shown in the post-use box in the figure) represents the concept of *industrial ecology* within a product's lifecycle. Industrial ecology, popularized within the engineering industry by Dr. Robert Frosch of Harvard University in the late 1980s, presents a scenario in which the entire industrial system behave similar to an ecosystem, in which "wastes of a species may be a resource to another species" (Frosh et al., 1989). Such a model requires multiple organizations working together within a systems-orientated framework. Furthermore, industrial ecology models industrial design and manufacturing processes as living organisms within a product development environment in which these development phases "are not performed in spoliation from their surroundings, but rather are influenced by them and, in turn, have influence on them" (Graedel et al., 1993).

In the past the concepts of recycling, in general, has always been assumed to be better for the environment because the use of virgin materials is obviously reduced.

A Swiss group conducted a simplified LCA to answer the question of whether the WEEE recycling program was actually increasing environmental performance of the electronics market. It was concluded that a take-back and recycling system for WEEE as established in Switzerland had clear environmental performance advantages as compared with the traditional approach of extracting virgin materials and processing brand new products. Furthermore, the group continued by explaining that even if incineration for the baseline scenario was ignored, the recycling program still outperformed the alternative (Hischier et al., 2005). Assessing postuse scenarios is still an ungoing area of research. However, in general, the avoidance of virgin materials shows great promise in reducing industry’s consumption and ecological footprint.

Product Design and Sustainability

Since decisions during the product design phase account for nearly 70% of the entire cost of a product’s development, it can be inferred that the ecological footprint is significantly fixed based on these decisions. By the detailed design phase, i.e. when dimensions, tolerances, and geometrical features of a product/process are known, there are few options to minimize the environmental impact (e.g. dematerialization, production optimization, efficient transport routes, etc.). Simply put, the design of a product strongly predetermines its behavior in the subsequent life cycle phases. For example, a highly modular design will bias the chosen end of life strategy towards reuse or remanufacturing. Figure 3 illustrates this general paradigm. Though the production and use phases of most products dominate its total environmental impact, these impacts are “committed” well before the development process reaches these key stages.

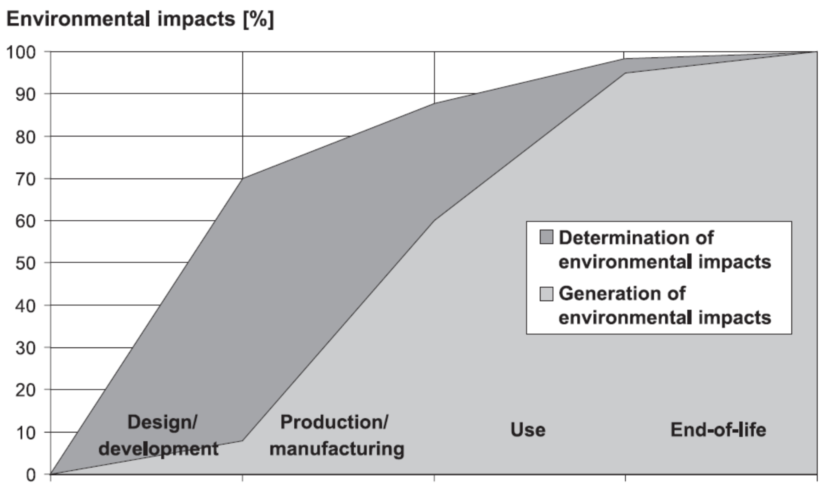

Figure 3: Generalized representation of the predetermination of the generation of environmental impacts in a product’s life cycle (Rebitzer, 2002)

Though these strategies can sometimes greatly reduce the eco-footprint of a product/process, it does not, for certain, provide an optimal solution. For example, developing a modular product system that institutes additional postuse operations must include justification for these added processes that they, themselves, might have negative effects on the environment. Hence, it is imperative to develop and practice eco-design tools that are relevant at the conceptual design phase. There have been computational and knowledge-related impediments in the past which has considerably stalled the delivery of such tools. With recent developments from the qualitative side (e.g. QFD-based tools, production checklists, LiDS wheel), specific corporate needs have shed light on the requirements of an effective methodology. Unfortunately, a holistic, easy-to-use, objectively driven conceptual design tool has yet to be developed as seen in Figure 4.

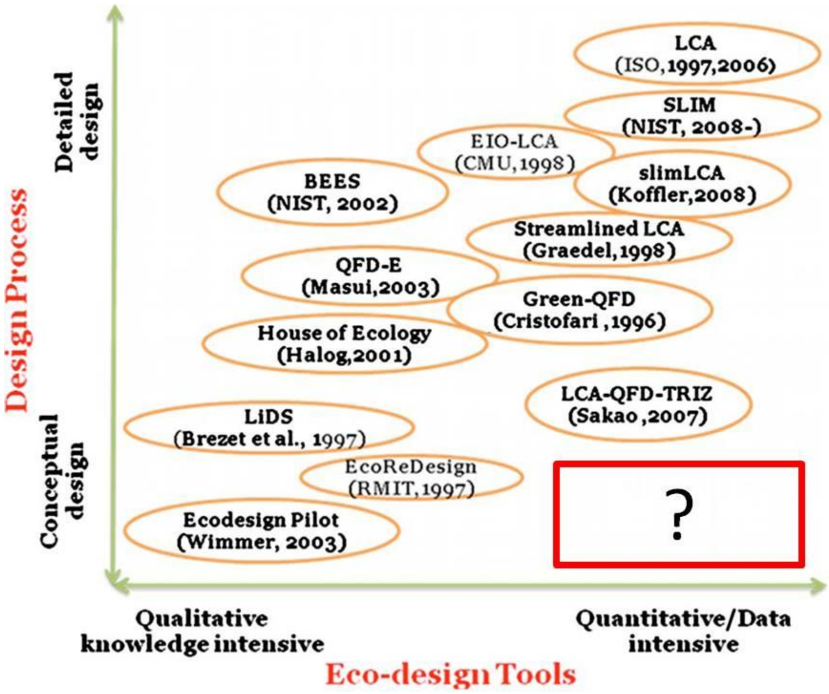

Figure 4: Map of current ecodesign tools showing the lack of quantitative/data intensive methodologies relevant to conceptual design (Ramani et al. 2010)

Fortunately, there has been numerous tools and methodologies developed to assist designers (1) in a qualitative manner at the conceptual design phase as well as (2) from a data intensive perspective during and after the detailed design stage.

Life Cycle Assessment

The most holistic, objective, data intensive tool for analyzing a product's life cycle is life cycle assessment (LCA). As seen in Figure 3, LCA is used once the details of a design are fixed, usually for compliance purposes. Though LCA is an extremely powerful tool, it is very exhaustive in terms of cost, time and labor. However, it remains the most widely accepted means to accurately calculate a product's or process's environmental impact. LCA is a methodological framework for assessing the environmental impacts attributable to the life cycle of a product. Figure 3 illustrates the general layout of a LCA.

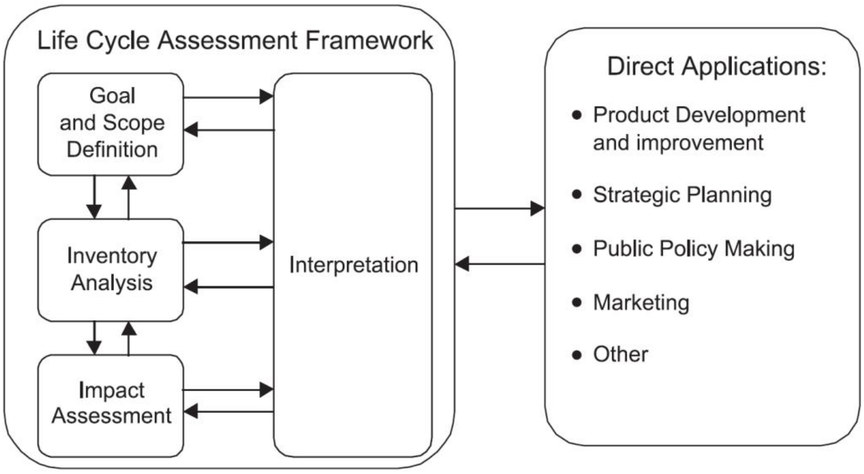

Figure 5: Phases and applications of an LCA (based on ISO 14040, 1997).

Goal and Scope Definition

The first step of a LCA is the goal and scope definition (Rebitzer et al. 2003), which is crucial for (1) identifying the purpose the study, (2) setting the system boundaries, (3) defining the functional unit and (4) determining the presented outcomes of the study depending on the stakeholders. This stage is particularly significant when constructing comparative LCAs of similar yet different products or processes. For example, when comparing the environmental impact of a nuclear power plant and a traditional coal-burning power plant, it is important to compare both systems with a common measure, such as the impact of generating 1 MW of electrical power.

Because the environment is a global constraint that affects many different lifecycle phases from a variety of external systems, it is imperative to explicitly state the purpose of the study. The wide range of inputs (e.g. energy sources, virgin materials) and ecologically related outputs (e.g. airborne emissions, solid waste, energy waste) makes it crucial to also clearly define the system boundaries. For an example, a consulting firm was hired to perform a LCA on a forest machine that cuts, stores and transports lumber. It is obvious to take into consideration the actual material required to build the actual machine, but what about the CNC machinery required to drill the holes, sockets, and features of each component? Does the firm consider the material required to build the trucks and aircrafts necessary to deliver the finished product to the customers; what about the production line for the trucks? These questions might seem trivial, but it is necessary to clearly define one's system boundaries to complete a LCA by ISO14040 standards. Along with the system boundaries, one must also state all related assumptions and study limitations (e.g. estimated, measured, or calculated data).

Additionally, according to ISO standards, the functional unit must be defined at this phase of the LCA. The functional unit is a measure of the function of the studied system, which provides a clear reference to which the inputs and outputs can be related. For instance, the functional unit for a computer monitor may be defined as a 17-inch color computer monitor with six years of lifetime (Kim et al., 2001). This makes it possible for two different brands, models, or configurations of a 17-inch monitor to be compared.

Finally, the actual outcomes of the study, including the type of impact assessment methodology and interpretation, must be presented. Since every product/process is unique with respect to its energy and material inputs, as well as environmental outputs, it is necessary to fix the rigor of the LCA (i.e. midpoint LCA or endpoint LCA). According to the US EPA (Environmental Protection Agency), a midpoint impact assessment model reflects “the relative potency of the stressors at a common midpoint within the cause-effect chain. Analysis at a midpoint minimizes the amount of forecasting and effect modeling…thereby reduction the complexity of the modeling and often simplifying communication” (EPA). In other words, the outputs of the lifecycle inventory are not normalized; they are simply presented in their respective units (e.g. kg of CO2, KW of energy waste, liter of solid waste, ozone depletion potential). Endpoints, on the other hand, define the actual physical, health damages to both humans and the ecosystem (e.g. risk of skin cancer, crop damage, marine life damage, cataracts, immune system suppression) (EPA).

Life Cycle Inventory Analysis

The life cycle inventory (LCI) of a product system is largely determined on the goal and scope (i.e. the system boundaries) of the environmental analysis. This data set is a compilation of inputs and outputs related particular functions of the product/process studied. Figure 5 illustrates a simplified schematic of the life cycle inventory analysis (LCIA).

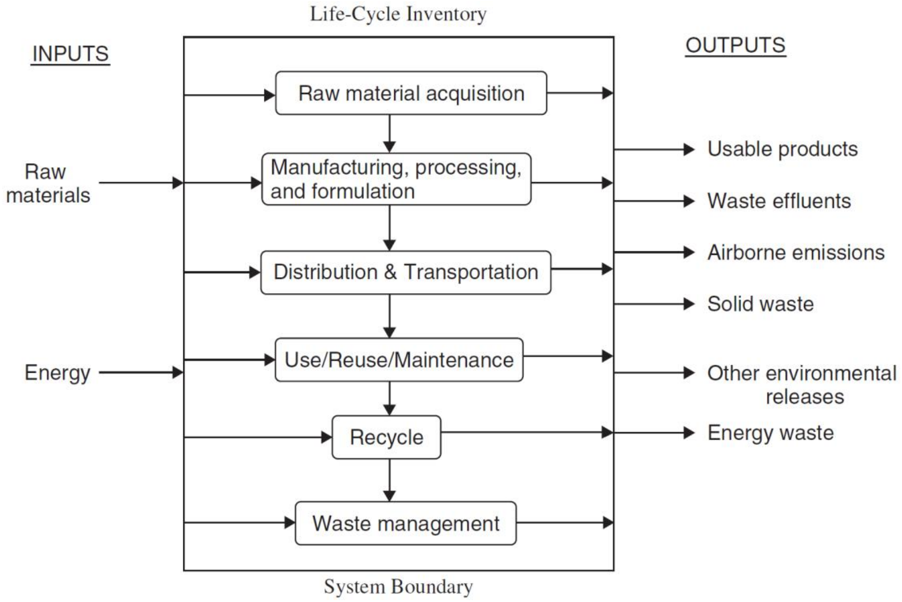

Figure 6: The life-cycle assessment (LCA) framework suggested by SETAC (Sridhar, 2007)

The primary challenge within this stage of the LCA lies within the actual data collection. One option, if possible, is to actually measure material and energy inputs. In other words, if a component within the studied product system requires 10 kg of rolled AISI 1020 Steel with several drilling and milling operations, one could measure the observed energy usage from the CNC mills. Depending on the percent contribution of these material requirements relative to the entire system, it might be more practical and efficient to use available databases for estimated energy usages. In general, product systems contain process types usually similar to benchmarked products, e.g. energy supply, transport and waste treatment services. As a result of shared, global markets, many of these process types are sometimes even identical, e.g. extracting oil in the Middle East or manufacturing various steels in Asia. Other processes consistently reflect regional properties, e.g. electricity generation, road transportation, cement manufacturing, and agricultural production. Therefore, databases providing high-quality data of frequently used commodities for LCIs are helpful and required, particularly if one wants to perform LCAs on a routine basis (Rebitzer et al., 2004).

Impact Assessment and Interpretation

The third phase of a LCA is coined the life cycle impact assessment (LCIA). This stage's goal is to evaluate the contribution of outputs derived from the LCI to specific impact categories (e.g. global warming, acidification, ozone depletion, etc.). It should be noted that LCIA at this stage is not an analysis of the environment outside of the system, i.e. the environmental effect. The next step within the LCIA is characterization, which begins with the common chemical properties of the emissions for each category and ends with indicators. Indicators are simplified estimates of emissions, waste, and resource use, which can be aggregated, weighted and normalized. This makes it possible for different impact categories from various product lifecycle stages to be effectively and easily compared (Owens, 1999). It should be noted that different LCIA databases (e.g. TRACI, EcoInvent 2.0) provide different weighting schemes for the respective impact categories. Depending on the specifics logistics of the product system, an appropriate database should be chosen. For example, TRACI was developed by the US EPA based on US empirical models; hence, product systems developed, used, transported and/or manufactured within the US should use TRACI as a LCIA database.

Example of LCA

The following LCA example was conducted at the Korea Advanced Institute of Science and Technology (KAIST) for a personal computer including its optimal recycling rate. The group defines the functional unit of the study as a personal computer made, used, and disposed of in Korea. The computer has a four-year lifespan and includes an Intel Pentium IV 1.7 GHz, 128MB RAM, hard disk drive (HDD), CD-ROM drive, GB hard disk, power supply, 3.5” floppy disk drive (FDD), modem, and keyboard all manufactured in Korea in 2001. To build the life cycle inventory (LCI), various databases were utilized, as well as calculated estimations and use of public data. The impact categories chosen for this study were abiotic depletion (ADP), global warming (GWP), exoxicity (ET), human toxicity (HT), acidification (Acid), depletion of the stratospheric zone (ODP), photoxoidant formation (POCP), and eutrophication (Eut) (Choi et al., 2006).

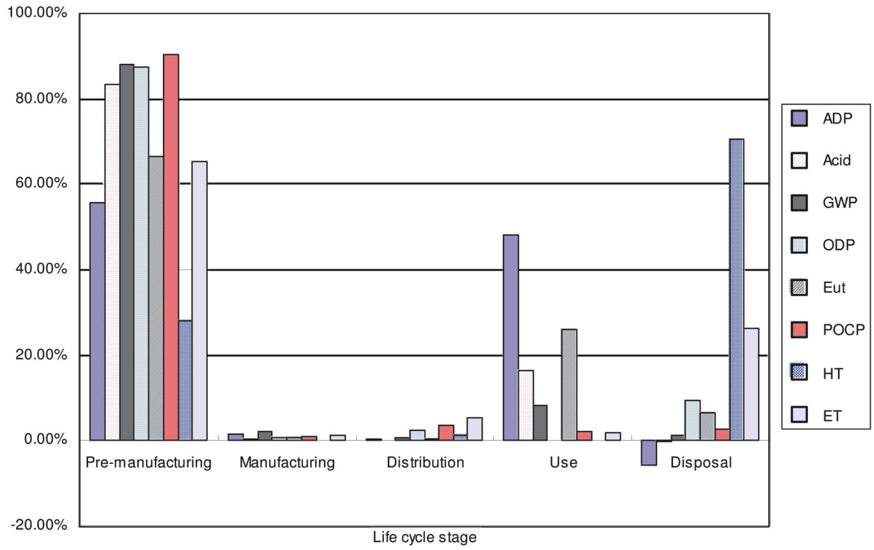

Figure 7: Environmental impact assessment result for a personal computer (Choi et al., 2006)

Figure 7 highlights the LCA results from the paper. As seen in this case, the pre-manufacturing stage dominates the entire environmental impact of the entire product. It should be noted that, in this study, the group considered the manufacturing stage as simply the aggregation of assembling the electrical components and packaging the PC for shipping. All production of individual components (i.e. mother board, CD drive, etc.) was accounted for in the pre-manufacturing stage. Manufacturing hundreds of small electrical parts will always be a solid contributor to global greenhouse gases, hence the heavy spike in GWP during pre-manufacturing. It should also be noted that production of electronic parts and the sulphuric acid and other compounds emitted when dealing with PCBs (printed circuit boards) heavily contributes to photoxoidant formation, as seen in the salmon colored bar. Furthermore, lead-soldering PCBs and other electrical parts contribute significantly to the acidification peak. During the use phase, all outputs were a result of the use of electricity produced by fossil fuels. This accounts for the significant contribution to abiotic depletion as well as eutrophication. Finally, the large spike in human toxicity at the disposal stage is due to the eventual land-filling of the product. One can also see the payback within the disposal stage due to recycling used materials.

Qualitative Design Tools

Since the early 1990s, qualitative ecodesign methodologies have been key corporate strategies with certain industrial sectors. These tools provide flexibility in that they are mostly subjectively driven by specific organizational goals and perceptions. For the same reason, criticism of the qualitative nature of these various tools has been recently evident throughout research communities. However, due to their relatively extensive industrial use of nearly 20 years, qualitative design tools have become somewhat of staples within in the industrial arena. In general, these tools can be classified into two high-level categories: (1) tools based on checklists and (2) tools based on QFD (quality functional deployment).

Tools based on checklists

These qualitative tools are the easiest to use and are among the tools most prevalent in industry, especially in small and medium size companies (Luttropp et al., 2006). A common feature of these tools is the checklist, which is a set of items used for assessing a product from an environmental perspective over its entire life cycle. These items include, for example, “is less energy consumed during the use phase of the product than the existing ones?” or “are less toxic materials used in the product?” (Otto et al., 2001). These tools are developed particularly for the early stages of the product development process. Compared with LCA, these tools are much more subjective. There have been recent efforts to develop more advanced checklists that include weights for the importance of the specific product requirement and potential eco-related improvements. These methodology provide more objective measures to a subjective methodology (Kishita et al., 2010). Table 1 shows an example of such a checklist developed by Hans Brezet and Caroline van Hemel.

Table 1: An Ecodesign Checklist by Hans Brezet and Caroline van Hemel (1997)

THE ECODESIGN CHECKLIST

Needs Analysis

- **How does the product actually fulfil social needs?**
- **What are the products main and auxiliary functions?**
- **Does the product fulfil these functions effectively and efficiently?**
- **What user needs does the product currently meet?**
- **Can the product functions be expanded or improved to fulfil users’ need better?**
- **Will this need change over a period of time?**
- **Can we anticipate this through (radical) product innovation?**

Production and Supply of Materials and Components

- **What problems can arise in the production and supply of materials and components?**
- **How much, and what types of plastics and rubber are used?**
- **How much, and what types of additives are used?**
- **How much, and what types of metals are used?**
- **How much, and what other types of materials (glass, ceramics etc) are used?**
- **How much, and which type of surface treatments is used?**
- **What is the environmental profile of the components?**
- **How much energy is required to transport the components and materials?**

In-House Production

- **What problems can arise in the production process in your own company?**
- **How many, and what types of production processes are used (including connections, surface treatments, printing and labelling)?**
- **How much, and what types of auxiliary materials are needed?**
- **How high is the energy consumption?**
- **How much waste is generated?**
- **How many products don’t meet the required quality norms?**

Distribution

- **What problems arise in the distribution of the product to the customer?**

- **What kind of transport packaging, bulk packaging and retail packaging are used (volumes, weights, materials, reusability)?**
- **Which means of transport are used?**
- **Is transport efficiently organised?**

Utilisation

- **What problems arise when using, operating, servicing and repairing the product?**
- **How much, and what type of energy is required, direct or indirect?**
- **How much, and what type of consumables are needed?**
- **What is the technical lifetime?**
- **How much maintenance and repairs are needed?**
- **What and how much auxiliary materials and energy are required for operating, servicing and repair?**
- **Can the product be disassembled by a layman?**
- **Are those parts often requiring replacement detachable?**
- **What is the aesthetic lifetime of the product?**

Recovery & Disposal

- **What problems can arise in the recovery and disposal of the product?**
- **How is the product currently disposed of?**
- **Are components or materials being reused?**
- **What components could be reused?**
- **Can the components be disassembled without damage?**
- **What materials are recyclable?**
- **Are the materials identifiable?**
- **Can they be detached quickly?**
- **Are any incompatible inks, surface treatments or stickers used?**
- **Are any hazardous components easily detachable?**
- **Do problems occur while incinerating non-reusable product parts?**

Source: Brezet, H. and van Hemel, C. *Ecodesign, A promising approach to sustainable production and consumption.* Edited by UNEP. Paris, 1997.

Tools based on QFD

The objective of a traditional QFD is to convert customers' needs into engineering characteristics and, at the same time, to improve the quality level of the product. By introducing the environmental impacts of the product itself and over its life cycle into QFDs as new customer needs, a set of ecodesign tools has been developed. These include QFD for the environment, green quality function deployment, and House of Ecology (Masui et al., 2003). In general, the application of these tools starts from collecting both customer needs and environmental needs and developing correlations between these needs and quality characteristics. A functional analysis is then performed to identify how quality characteristics are correlated with engineering characteristics, including structure or components and hot spots from both environmental as well as traditional quality points of view. It can be seen that QFD-based tools are significantly different from a LCA since the focus here is on the product specification development stage. It should be noted that the development of correlations between environmental needs and quality and engineering characteristics rests solely on the designers, and usually the correlations developed are based on knowledge from the traditional environmental engineering discipline and sometimes, unfortunately, without the consideration of the entire life cycle (Bouchereau et al., 2000).

Computer Software Packages for Ecodesign

Probably the area that has the highest potential of successfully incorporating sustainable design principles into an existing engineering design framework is within computer-aided design (CAD) packages. Three efforts to embed ecodesign within software are Dassault Systemes' Solidworks^{TM} Sustainability Xpress, Granta Design's Eco Audit Tool (CES Selector), and Sustainable Minds®. Figure 7 is comprised of screenshots of each of these tools.

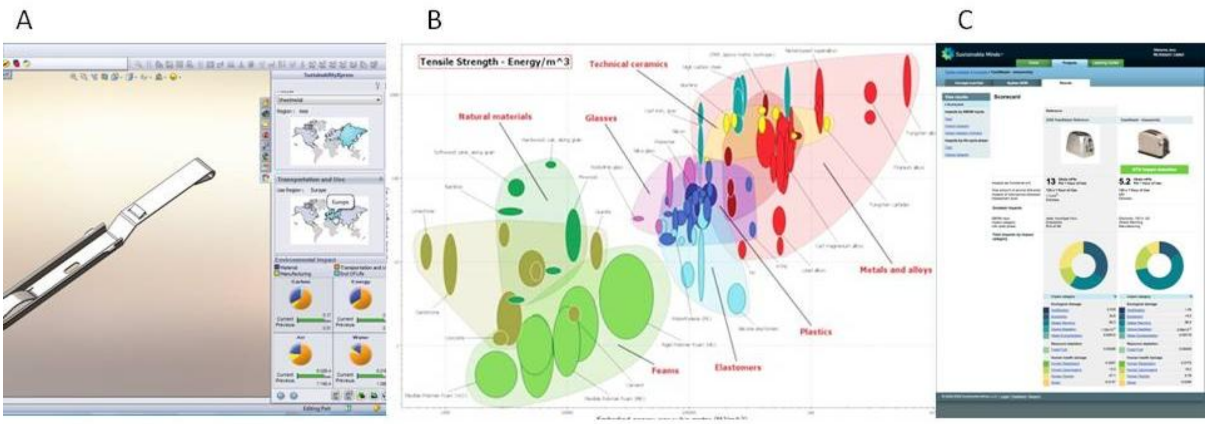

Figure 8: Screenshots of software tools aimed at ecodesign – (A) Dassault Systemes' Solidworks^{TM} Sustainability Xpress (B) Granta Design's Eco Audit Tool and (C) Sustainable Minds®.

Each software depicted in Figure 7 provides designers with different advantages. Solidworks^{TM} Sustainability Xpress offers estimate environmental impacts associated with the material and manufacturing selections chosen by the user. For detailed design, this tool is most applicable, but complete dimensions and tolerances are required to run the simulation. Hence, if there were another possible design embodiment to meet the same requirements as this design, it is not possible to estimate its potential ecological footprint without a full-scale CAD model. Granta Design's Eco Audit Tool takes advantage of Granta CES Edupack, a material database that has been in development for some 15 years and contains precise, detailed datasheets for over 3000 materials, including casing energy (MJ/kg) and carbon footprint of materials (kg CO2/kg). Once again, this tool is mostly relevant for the detailed design phase for the same reasons as Sustainability Xpress. Sustainable Minds® provides a smooth GUI (graphical user interface) in which designers can run LCAs and see tradeoffs between two designs of a product. A step in the right direction, Sustainable Minds® offers the same capabilities as SimaPro with more attention to user needs.

End-of-Life Management: Extending the Life Cycle

Managing end-of-life (EOL) products has become a field of rapidly growing interest for product manufacturers. As environmental regulations urge stronger stewardship for product retirement, disposal can no longer be the primary retirement strategy for end-of life products. Manufacturers need to find more proactive ways to reduce waste and save resources. EOL management of used products is a promising solution to this problem. EOL management is the process of converting EOL products into remarketable products, components, or materials. Product design features, such as product architecture, material properties, functional performance, and reliability, greatly affect what types of used products can be collected, what kinds of recovered items can be produced, what recovery operations are necessary to produce them, and how profitable the recovered units can be. Therefore, EOL management should be considered at the design stage in order to facilitate efficient and effective take-back and recovery.

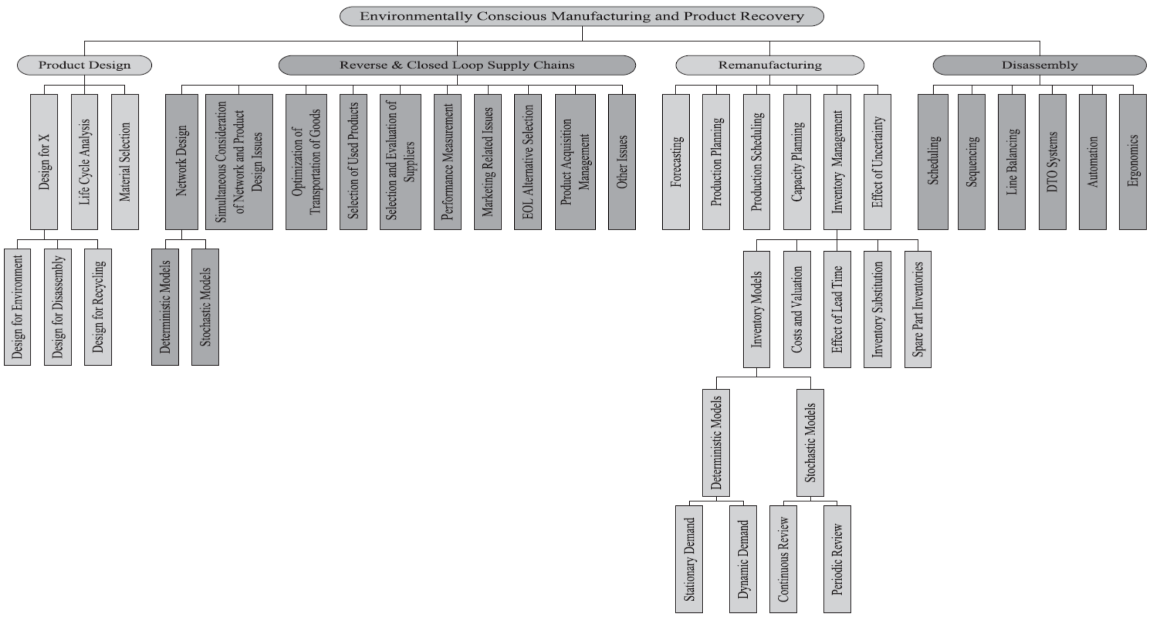

Figure 9: Classification of issues in environmentally conscious manufacturing and product recovery (Ilgin and Gupta, 2010)

Product Service Modularity

For the past two decades, modularity has been a key focus to extend the product's lifecycle not only from an end-of-life persective, i.e. optimizing EOL decisions for separate subassemblies, but also for service and maintenance during the use phase. Three main aspects should be considered with respect to service modularity to realize its full benefits: (1) maintaining independence between components in different modules, (2) encouraging similarity in all components in modules, and (3) maintain interchangeability between modules. Its argued that focusing on these three key aspects, a product can be flexible to changes in service procedures, which in turn will lead to a decrease of the lifecycle service cost of the product (Gershenson and Prasad, 1997). Though it has never been proven that modularity in the form of structure, production, and service has a direct correlation with the product's sustainability. It is clearly safe to assume that modularity, overall, extends the product lifecycle and this augments sustainability.

Gershenson and Prasad (1997) present four facets of modular product design and show how each correlates to product maintenance and serviceability.

1) *Attribute Independence:* Features within a particular module have a small number of dependencies on external relationships with other modules. This allows easier redesign operations within a specific module without affecting other forms (or modules) with respect to the entire system (or design). An example of the opposite of attribute independence, attribute dependence, is a design that contains multiple electrical components that are powered by the same electrical connection. Redesigning the power inlet for one module requires redesign considerations of other modules, increasing the cost of serviceability.
2) *Process Independence*: Process, here, refers to the process of service. In other words, each service for a module has fewer dependencies of service operations with respect to other modules. An example of process dependence would be a computer outer casing and the mother board. To service the mother board, it is required to remove the outer casing of the computer system.
3) *Process Compatibility:* Within a module, multiple service modes should be compatible in terms of failure time, complexity, and feasibility. If components within the same module have life spans of 2 and 10 years, respectively, there exists little process compatibility with respect to servicing. This could lead to unnecessary disposal of acceptable components.
4) *Process Uniqueness:* It is beneficial to group subassemblies and/or components that have the same service modes in the same module, where possible. This, in turn, deceases cost at service and increases the overall modularity of the system significantly.

Part Standardization

End-of-life management involves multiple types of end-of-life products. Accordingly, product take-back and end-of-life recovery are influenced by individual product designs and the interactions among designs. Increasing part commonality across product variants can benefit end-of-life management in two ways. First, the economies of scale in the recovery operation increase. Necessary tools and worker skills and setup time decrease in various recovery operations, including disassembly, repair, and reassembly. Second, the interchangeability of components across product variants increases, which in turn facilitates part reuse (Simpson, 1998) (Perera et al., 1999) (Bras, 2007).

Take-back Management

Product take-back is emerging as a critical area to ensure sustainable product design and EOL management. Product take-back has been examined mainly from business and operational perspectives. Uncertainty of quality, quantity, and timing of end-of-life products makes EOL management difficult (Guide, 2000). Active take-back can be used to mitigate such uncertainties. The active take-back system provides consumers with economic incentives if they return EOL products in good condition in a timely fashion. In this vein, pricing of used products and designing a trade-in or buyback program are of interest, and these concepts need engineering design involved for better decisions (Ray et al., 2005).

In the past, most product take-back models were focused on optimizing facility locations and resource allocation in order to minimize costs. Recently, however, novel supply chain models started adopting product design focused variables in addition to location and allocation information in order to optimize LCA results. A set of works addresses the problem of scheduling take-back. The demand for parts or recovered products triggers product takeback, and the objective is to fulfill the demand at minimum cost. Key decision variables are the amount and type of cores to acquire and the amount and type of parts to externally procure. Research connecting the design perspective to business and operational perspectives is necessary. Also, product design for a timely take-back is necessary (Ramani et al., 2010).

Reuse and Remanufacturing

The economic benefits of remanufacturing have been well established in the research community. In fact, it has been reports that the automotive industry could save an annual energy equivalent of five nuclear plants by adopting remanufacturing pathways (Steinhilper, 1998). In light of recent regulation demands, remanufacturing is “a promising corporate strategy to reduce energy consumption and decrease CO2 emissions” (Sutherland et al. 2008). A hot area of research has been the development of design metrics for assessing the remanufacturability of product designs. In order for profitable reuse and remanufacturing, a product design should have efficiency in assembly, disassembly, testing, repair, cleaning, inspection, refurbishing, and replacement (Hammond and Bras, 1996). Qian and Zhang (2009) defined eight “environmentally conscious modularity criteria” to develop an all-encompassing modularity score:

1) *Usage Life Compatibility*: When components have significantly longer use cycles within a module, replacing the entire module becomes wasteful.
2) *Technology Life Compatibility*: This metric is based off the technological experiences throughout a product's life cycle: introduction, maturation, and obsolescence. This speaks to the upgradability of outdated modules.
3) *Material Compatibility*: This requires that similar or compatible materials be used in the construction of components, modules or products. Ultimately, a higher material compatibility makes it much easier and cheaper to manufacture, assemble/disassemble, and recover/recycle.
4) *Maintainability*: Modules should be easily separated and maintained during the use phase in order to extend the usage life of the entire product.
5) *Geometric Connection*: Because ease of disassembly is such an important aspect of DfE, a design should have geometric connections between modules to be easily broken without damaging other modules.
6) *Disassembly Time*: Time to disassemble directly correlates with ease of disassembly.
7) *Disassembly Energy*: A measure of effort, in terms of mechanical power, to disassemble modules from the core product.
8) *Easy-to-Assemble*: The authors add this metric in the case of special connection points, such as snap fits. Snap fits are very simple to assemble but rather difficult to disassemble.

Recycling and Material Recovery

The economic viability and environmental impact of material recovery are directly influenced by the materials used. Reducing material diversity in a product, using less toxic materials, and employing biodegradable material are well-known design guidelines applicable in the design stage. Many approaches have been developed to help designers choose the proper material by considering all economic, environmental and technical perspectives. Using Ashby Charts, as seen in Figure 10, is one such approach (Weaver et al., 1996). Product structure is also an important factor affecting material recovery. To be specific, modular design is desired, which supports easy separation of different material types.

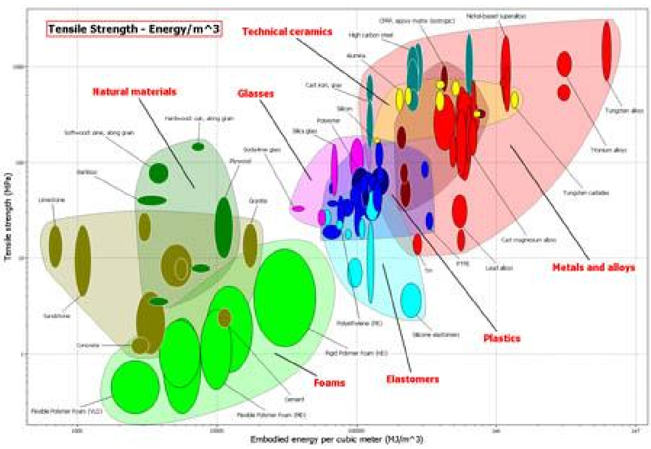

Figure 10: An example of an Ashby chart (CES Edupack 2009)

Studies have been carried on to further investigate the notion of modularity and its direct benefits on the efficacy of a reverse logistics framework. Fernandez and Kekale (2005) conducted a literature review encompassing multiple industrial case studies specifically investigating the relationship of product modularity and "industry clockspeed" (i.e. the speed of change within an industry that influences a company's new product development activities as well as the existing product's life cycle length) on reverse logistics strategies. The paper reached three conclusions:

1) A short clockspeed and a product with limited modular architecture alone or in combination complicate reverse logistics. Varying clockspeeds in individual modules also increases the relative difficulty in the organization of subsequent recovery, repair, and reuse functions.
2) The higher the degree of modularity, the more opportunity there is to recover parts of the product economically, although under a certain level there does not seem to a viable recovery alternative. In other words, as first hypothesized, modularity directly relates to the recoverability of a product.
3) For every organization, there is a company-specific optimal clockspeed at which a reverse logistics framework would operate rather seamlessly.

Description and model of production system life cycle

The product manufacturing process consumes resources directly and produces environmental pollution. It has a significant impact on the result of enterprise performance in terms of sustainable development (Gutowski, 2004). Since traditional manufacturing processes are designed specifically for high performance and low cost, little attention has previously been paid towards environmental issues. Efforts to minimize the environmental impact of a system's production can be roughly classified into three categories: (1) process improvement and optimization, (2) new process development, and (3) process planning as detailed in Figure 8.

Process Improvement and Optimization

Traditional manufacturing process optimization has traditionally focused on variables such as cost, cycle time and tool life. There have been several studies which have discussed on the type of correlation between such traditional optimization parameters and sustainability (Klassen, 1999). Current studies have focused on addressing this issue by optimizing the process for manufacturing energy consumption, or the net environmental impact of this stage. One such example of reducing the environmental impact of the production phase through process improvement can be seen within the machining process. Metalworking fluids are widely used in a variety of machining operations, with flood delivery being common practice. Skerlos et al. have reviewed advances in the development of metalworking fluid delivery strategies for sustainable manufacturing. An improved coolant subsystem which simultaneously reduced health risks, resource consumption, emissions and improved overall performance was proposed. This was achieved either by extending the lifetime of water-based fluids dramatically or, better yet, by switching to gas-based systems (air or supercritical carbon dioxide) in order to minimize lubricant quantity (Skerlos et al.

2004). Sustainability performance analysis using virtual machining models is another promising approach for process improvement. The ability of modeling and simulation of the manufacturing process to predict the effect of implementing certain facility, process and product actions and analyzing the environmental impact makes it an ideal platform for assessing and improving manufacturing sustainability (Shao et al., 2010). The current research focus in this regard is to integrate sustainability analysis within existing simulation engines such as Siemens NX, Step-NC etc.

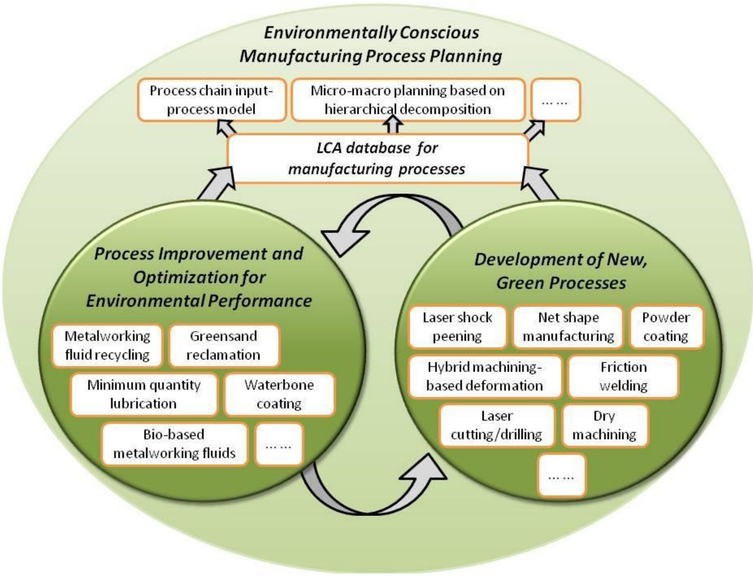

Figure 11: Sustainable Manufacturing

Modelling and simulation needs to extend much further than just point manufacturing process. In other words, understanding manufacturing from a factory and network level carries heavy significance in developing optimally efficient systems. Especially with the rapid advance of electronic and communication technologies, modelling and testing agile, vitual and distributed manufacturing networks that can share information and resources even among loosely connected firms carries tremendous value (Lee and Lau, 1999).

Novel Green Process Development

Besides process improvement and optimization, many new “green” processes have been developed to replace conventional processes. One example is the development of LASER based manufacturing processes. LASER cutting, which has become a popular alternative to Oxy-fuel cutting usually leads to much narrower widths of cut and thus wastes lesser material. Moreover, it does not emit toxic metal oxide fumes. Similarly LASER shock peening has become competitive with conventional shot peening for certain aerospace and aeronautic applications, where high residual stresses and long fatigue life are desired. Compared with shot peening, laser shock peening does not consume a shot medium; thus, no particulate emission is involved. Similar examples include the development of water jet machining and zero-waste additive manufacturing processes such as 3D printing ad Stereolithography. It should be noted that LCA needs to be conducted to confirm the “greenness” of the new process (Zhao et al. 2009).

Process Planning

As seen in Figure 8, process planning plays a key role towards achieving sustainable development. The manufacturing plan outlines the selection of the manufacturing processes, sequencing of the processes, and parameters for each manufacturing process. Similar to in product design, one can argue that in the early stage of process planning, selection and sequence of major processes are more critical than the parameter optimization of processes involved, with regard to performance, including that of sustainability. Process planning is conventionally completed manually from scratch by experts who retrieve and manipulate a great deal of information from many sources, including established standards, machinability data, machine capabilities, tooling inventories, stock availability, and existing practice. Sustainability considerations in terms of energy efficiency have been introduced into computer aided process planning (CAPP) to complement cost, quality and time to arrive at alternate sustainable plans or schedules in an identified manufacturing process (Mani et al. , 2008). Similar to computer-aided design Computer aided design (CAD), CAPP when combined with Computer aided manufacturing (CAM) is effective in optimizing processes in a selected sequence. However, it usually offers limited help at the early stage of process planning. To date, only a handful of papers have been published, which focus on the integration of environmental considerations into early process planning. Furthermore, due to the lack of life cycle data of manufacturing processes, almost all of the papers have directed their efforts to framework or methodology development. Holistic integration of environmental considerations into manufacturing process planning will allow for more sustainable manufacturing process selection and inventory management.

Factory-level and Network-level Considerations

Most of the discussion above within WP6-2 has been focused on improving tooling within production in order to achieve sustainability. Of course, a different, more top-level approach, is possible as well. From this perspective, most of the state-of-the-art practices are focused on minimizing energy consumption both the network and factory point-of-views. Intelligent Manufacturing Systems (IMS), an industry-driven international collaborative manufacturing research imitative, has taken on a project (IMS2020) to identify key research areas to realize for energy-efficient production techniques. IMS2020 has identified 5 key areas of focus: (1) sustainable manufacturing, products and services, (2) energy efficient manufacturing, (3) key technologies, (4) standardization, and (5) innovation, competences development and education (http://www.ims2020.net/). The first key area encompassing “sustainable manufacturing” is focused on utilizing takeback strategies to avoid virgin materials as well as other techniques that have been thoroughly discussed in this report. Hence, this section will focus on the IMS2020 guidelines for their second key area of research, energy efficient manufacturing.

One of IMS2020’s approaches for discovering and organizing the latest research trends and opportunities is via online surveys. Based on the surveys, the most significant topics were as follows (Park et al., 2009):

1) *Energy-aware Manufacturing Processes – Measurement and Control*
2) *Maintenance Concept for Energy Efficiency*
3) *Energy Efficiency Improvements through Efficient Use of Raw Materials*
4) *Using Energy Harvesting in Manufacturing Processes*
5) *Electrical Energy Operations in Off-peak Hours*
6) *Energy Efficient Particle Size Reduction*
7) *Energy Efficient Production Management Systems*
8) *Energy Autonomous Factory*
9) *Green Manufacturing for future vehicles*
10) *Advanced Automation for Demanding Process Conditions*
11) *Intelligent Utilization of Waste Heat*
12) *Product Tags for Value Chain Performance Improvement*
13) *Integrative Logistics Tools for Supply Chain Improvement*
14) *Framework for Collaboration in the Alternative Fuel and Raw Material Market*
15) *Technological Access to Wastes for Enhanced Utilization in Resource Intensive Industries*
16) *Emission Reduction Technologies*

For the most part, these 16 areas focus on the factory-level. In other words, they provide a context for the novel development of measurement as well as production tools to effectively increase energy efficiency of particular production modules. However, it should be noted that there are great opportunities for energy savings with respect to systems and networks of systems. Since calculating energy consumption of individual subsystems within a large manufacturing system, various engineering approaches have been developed to model energy flow and, ultimately, discover redesign opportunities in order to increase energy efficiency. From a network of factories point-of-view the concept of smart power grids is very relevant (Park et al., 2009). Investigating new methods to use electric energy at peak times of demand, securing device management protocols for broadband networks, investigating and trading electrical energy waste, and generally enhancing electrical energy reliability and capacities are all relevant areas of research.

Description and model of interaction between product and production system life cycles

To realize all best practices discussed in D6-1 and D6-2, organizations must understand the interactions and relationships between all lifecycle phases, most notably the correlation between downstream effects with upstream decision making. Knowledge management for product systems, hence, has had a direct impact on researching enablers for sustainable production. Figure 13 illustrates this paradigm of organizing outputted information from both the product life cycle and production system life cycle to understand independencies between the two significant development phases.

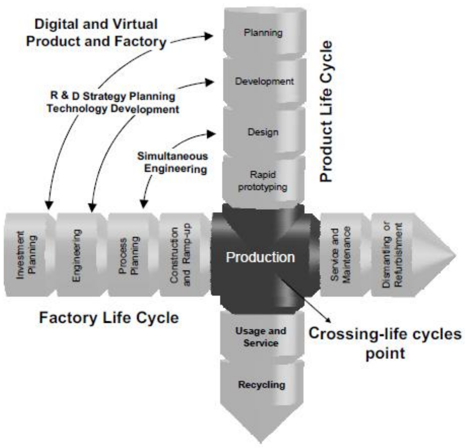

Figure 12: The harmonization of product and factory life cycles (Pedrazzoli et al., 2007)

Additionally, Supply chain effects as well as end-of-life interactions with the product life cycle could be key contributors to the system's total eco-footprint.

Life Cycle Management

Life Cycle Management (LCM) considers the product life cycle as a whole and optimizes the interaction of product design, manufacturing and life cycle activities (Westkamper et al, 2000). The goal in LCM is to conserve resources and maximize their usage effectiveness by means of Life Cycle Assessment (LCA), Product Data Management (PDM), Technical Support and Life Cycle Costing (LCC). The purpose of LCE is to design products in compliance with the key issues of sustainable development. The most efficient use of modern technical products demands the knowledge and know-how of the manufacturer while making use of "Technical Support" i.e. modern communication networks, tele-service and tele-operations. To discover the potentials for ecological improvement, LCA uses data of the physical product life cycle for evaluation. Life cycle assessment provides quantitative basic data for a sustainable product and process management in accordance with public pressure and, last but not least, economical constraints. LCC assesses not only the life time but also the costs of operation and other costs more efficiently but also leads to higher economic effects. Currently, it is hypothesized that cost-efficient solutions are inherently eco-friendly. Thus, LCC and LCA are used independent of each other. Data which is both precise and accurate is a prerequisite for assessing ecological and economical aspects. However, such data is usually too expensive to obtain. Hence, several models of LCA and LCC which account for data uncertainty have been developed.

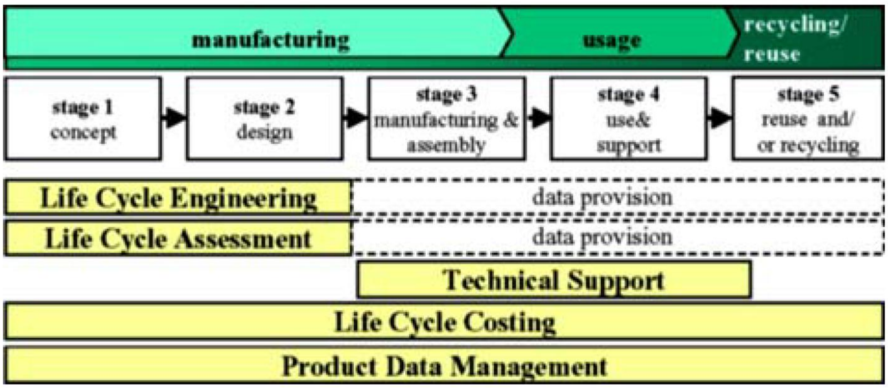

Figure 13: Application of LCM Methodologies (Westkamper et al., 2000)

Life cycle management organizes the interaction of the life cycle partners to achieve the maximum benefit from each technical product. The three main fields influencing the activities of the partners are environment, regulations and standards, as well as the constraints of economy. To achieve the best practice, the partners have to cooperate and tap into the know-how of all parties at all life cycle stages. To minimize the risks and to secure the maximum result, all of them should be part of the value adding processes depending on the extent of the value they contribute (Westkamper et al., 2000).

Life Cycle Simulation

Life Cycle Simulation (LCS) is a powerful tool for planning product architecture in perspective of its life cycle. An LCS system simulates the flows of products, materials, money and information based on a proposed life cycle model. The resulting information can then be used to select appropriate product architecture as per the chosen life cycle model. The architecture of a typical LCS system is illustrated below.

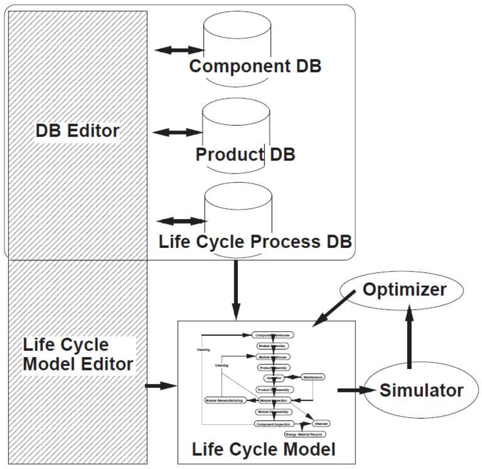

Figure 14: Architecture of an LCS system (Nonomura et al., 1999)

The life cycle simulator executes simulation of a product life cycle based on a given life cycle model using discrete event simulation techniques while the life cycle data base tool manages the data of products, components, and processes. The life cycle optimizer optimizes the value of parameters in the target life cycle model.

LCS is becoming the preferred tool for designing products with respect to inverse manufacturing. Scenarios of reuse, recycling or remanufacturing can be effectively generated and their performance measured with the aim of adopting the most suitable end of life option for closing the product loop. The advantage of LCS over conducting a Life Cycle Analysis (LCA) is that it requires lesser input data, which need not be precise. However, it cannot perform a detailed environmental analysis or point out specific environmental effects the product contributes towards, as detailed by an LCA (Nonomura et al., 1999).

Supplier Selection for Sustainability

Supplier selection has always been a heavy area of research. The risk associated with selecting an economically unstable supplier is tremendous and could even crumble the steadiest of product systems. Koplin et al. (2007) argues that now companies must identify new criteria for supplier selection and evaluation, aiming to integrate new environmental and social constraints with the traditional economical guidelines. This also includes implementing related control mechanisms and compliance stimuli to be passed on to suppliers (Koplin et al., 2007). Classifications and rating schemes for global suppliers would help neutralize corporations' concerns of the environmental impacts produced by their suppliers. Some standards, such as ISO 14001, have been developed but have yet to be dispersed across the industry from a global perspective.

In general, the issues directly related to supplier selection for sustainability against actual sustainability-oriented criteria is greatly lacking (Koplin et al., 2007). However, there has been some work. Hutchins and Sutherland (2008) developed a framework for supplier selection based on four social sustainability aspects (i.e. labor equity, healthcare benefits, workplace safety and philanthropic activities) by assigning weights to each aspect of each company. This, in effect, evaluated the social sustainability of a supply chain. Unfortunately, the relationships between business actions and their social resposses within a supply chain have yet to be characterized. Also, there has yet to be developed an effective methodology to balance the social responsible decisions for supply chain selection with the optimal economic choices.

Projecting Supply Chain Knowledge to Design

Though there have been some recent work developments attempting to predict supply chain data at the early design stage, this research area is still well in its infancy. The ambiguity associated with an embodiment design gives little insight into the dynamic networks associated with transportation, distribution, and other supply chain related costs. Additionally, linking product attributes and features directly to supply chain costs is challenging without having fully developed relationships among designers and manufacturers and/or suppliers. Efforts, such as the Walmart™'s Sustainability Consortium, aim to gain insight into these issues. Walmart™'s surveying 100,000 global suppliers to evaluate their sustainability is clearly a step toward enhancing transparency of supply chain networks to its customers (Walmartstores.com).

Though modularization and part/subassembly commonality across separate product lines or pipelines could significantly reduce the environmental costs of supply chain networks, innovative metrics and decision making tools for the product's early development stages are essential to deliver the necessary ecosavings. Clear identification of shipped products with barcodes is one example of facilitating logistical issues within product design by including specific features that inherently provide product knowledge (Thomas, 2009). Additionally, Harold Krikke of the Open University and Tilburg University leads a research group aimed at optimizing closed loop supply chains. In 2003, his group developed a volume-based mathematical model with optimization techniques to improve supply chain eco-costs for the design of refrigerators (Krikke et al., 2003).

In general, life cycle simulation (LCS) has emerged as a promising field to narrow the gap between supply chain cost estimation and design feature decisions. As of now, there has been little work with regard to DFE in simulating supply chain networks. However, there have been recent studies within LCS specifically for optimization of supply chain eco-costs, e.g. (Lily et al., 2009). The potential benefits of LCS with regard to environmental cost savings and application to decision making are significant. The supply chain's relative impact on sustainability within design remains as a potentially rich avenue for innovative research.

With the emergence of LCS, researchers have focused on incorporating information technologies with state-of-the-art sustainable development practices. Energy informatics, ICT-based decision support systems, advanced human/technology interfaces (from assembly as well as process perspective), modelling and simulation of advanced plant-wide control, simulated factory planning, LCA database mining, environmental analyses on virtually generated design embodiments, smart embedded product tracking systems and the integration of semantic knowledge management to support sustainable development are all examples of key research areas for the future of sustainable production. Utilizing computational power, these opportunities are key business drivers to gain a competitive advantage.

End-of-Life Decision Making

End-of-life (EOL) logistics are not solely based on the material makeup of the system in consideration. Structural modularity, for example, is a key component to assess a system's complexity of disassembly, which can easily make recovering certain components unfeasible and impractical. Various methods have attempted to objectively consider such intrinsic properties of products and systems. These metrics combined with design tools discussed in D6-1 will be key enablers to realize sustainable product development.

It is difficult to recommend a specific product recovery model over another since this heavily relates to different types of products and industries. However, OEMs' (original equipment manufacturer) direct product take-back and remanufacturing may be the most preferred model in the context of sustainable product design and recovery. In practice, it is unrealistic to expect OEMs to gather feedback from remanufacturers for design innovation and changes, as pointed out by (Jacobsson, 2000). Much research has been committed to understanding product recovery, including product EOL decision making for multiple life cycles, linking product recovery with design decisions, merging recovery networks with product design chains, sharing components or disassembly operations, among other related topics. However, an analysis of individual product is necessary to evaluate the efficacy of product recovery as product take-back largely depends on situational issues, e.g. transportation and energy grid technology (Skerlos et al., 2003).

Table 2: Remanufacturer business types and examples (Ramani et al., 2010)

Remanufacturer	Structure	Characteristics	Examples
OEM (Original Equipment Manufacturer)	OEM has full control over design and recovery.	• Effective compliance with environmental regulations • Economic benefits (if return volume is high) • Reuse of remanufactured parts and components. • Protection of OEM's proprietary design information.	Kodak, Fujifilm (single-use cameras), Caterpillar, Perkins engine (engine/transmission), Milliken (carpet), BT industries (Forklift trucks), Swepac (soil compactors), Electrolux (white goods, commercial cleaning equipment), Xerox (printers, copiers, HP, IBM (PC)
Subcontractor	Subcontractor provides remanufacturing service.	• OEM maintains product brand and warranty. • OEM can facilitate design improvement based on subcontractor's feedback. • Subcontractors can receive assistance from the OEM for parts, designing, and tooling.	Flextronics InfoTeam (Sony, Game console)
Independent Remanufacturer	No or little partnership exists between OEM and third-party remanufacturer.	• Remanufacturers often become competitors with OEM. • Remanufacturers need to purchase parts for recovery process.	Recellular (cell phones), 24 Hour Toner (toner cartridges), MKG Clearprint (toner catridges), Turbo tech (turbochargers)

Table 1 above categorizes three different remanufacturing pathways that have significantly different characteristics with respect to general logistics and partnerships. Even the timing of specific component takeback has become an issue of debate.

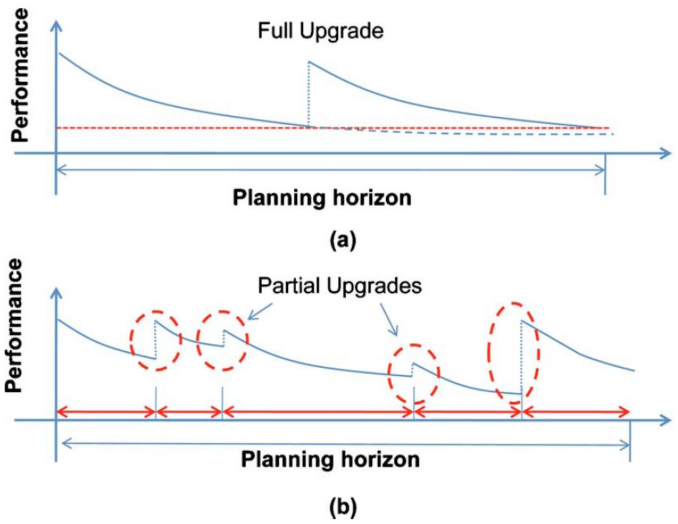

Figure 125: Effect of partial and complete upgrade on performance within specified planning horizon (Zhao et al., 2010)

Figure 9 illustrates two possible scenarios, in which the customer imposes a constraint in terms of the minimum acceptable performance, shown as the doted horizontal line. Depending on the product or system, it may be cost effective to provide partial upgrades to the product to maintain performance, illustrated in 2b, as opposed to one intensive, holistic upgrade, shown in 2a. Work has been conducted to suggest possible disassemble and upgrade pathways based on reliabilities of individual components/subassemblies. Of course, this model for a product system is only viable if there is significant planning at the design phase (i.e. modularizing subsystems, developing remanufacturing pathways, etc.). This same general idea has also been expanded to recycling, specifically selective disassembly and end-of-life decision making (Behdad et al., 2010). Both of these studies were conducted under the supervision of Professor Deborah Thurston from University of Illinois Urbana-Champaign, a leader in research methods regarding sustainable post-manufacturing product management.

A Sustainable Product Lifecycle Requires Organizational Learning

In conclusion, from a top level perspective, IDEO, a very well respected worldwide design and innovation consulting firm, argues that sustainable design/development can be described as a “learning orientation.” Because of the fluid, mutable and evolving nature of sustainability, involvement from various organizational levels and teams is a dynamic and progressive process. Each manager, designer, technician, etc., plays a significant role in a product system’s lifecycle from different angles with respect to time as well as space. To understand these complex interactions, each organizational level is obliged to consequently educate themselves in best practices. Figure 10 depicts this evolving process (IDEO, 2008).

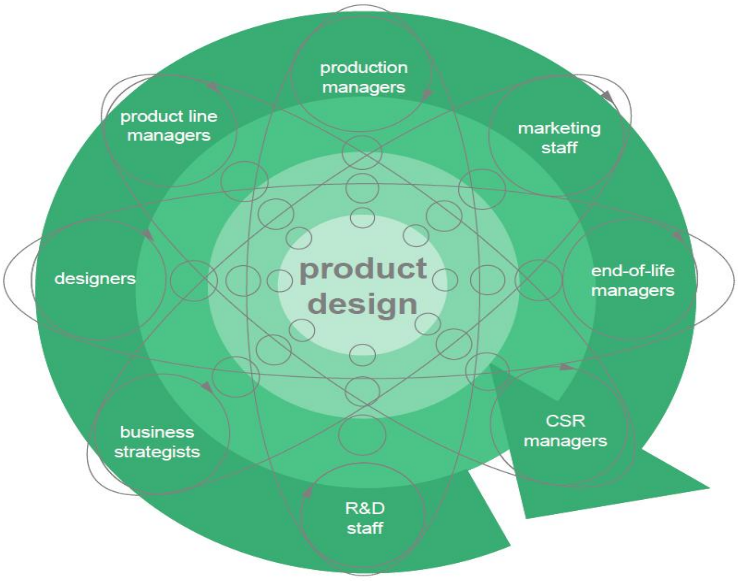

Figure 136: A diagram representing the design process evolution through sustainability intelligence. The paradigm shift is shown as growth from pale to dark green and from small involvements to robust and routine connections across functions (IDEO, 2008).

Furthermore, the lack of clear standards of sustainability throughout industry makes it unfeasible to create simple lists of input materials/products labeled as “good” green. Likewise, few resources can be clearly spelled out as “poor” options. With each new product, system, or process developed, new environmental constraints are created which may expose corporate misconceptions related to organizational sustainability. Hence, there exists an ever-growing challenge to understand these new constraints and develop innovative, effective solutions in the form of novel methodologies and user-centric tools.

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Introducing Sustainability Early Into Manufacturing Process Planning

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A comparison of manufacturing and remanufacturing energy intensities with application to diesel engine production John W. Sutherland (2)*, Daniel P. Adler 1, Karl R. Haapala, Vishesh Kumar 2 EPA
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Case study abstracts

Discovering Material Recovery Scenarios for Industrial Machinery

Bernstein W.Z., Ramanujan D., Koho M., Zhao F. & Ramani K. 2012 Proceedings of the 2012 ASME Manufacturing Science and Engineering Conference (MSEC2012), USA. June 4-8 2012.

Growing public concern regarding issues related to environmental sustainability is currently motivating a paradigm shift in design thinking within organizations. There is an imminent need to equip industrial manufacturers with novel design infrastructure in the form of easy-to-use tools that predict a product's net environmental footprint across its entire lifecycle (i.e. from material acquisition through its eventual disposal). Decision-making methodologies for evaluating a product's end-of-life options have become a significant area of research in light of these new requirements. Extensive research has been carried out in the area of product recovery, e.g. module-based disassemblability, reverse logistics, remanufacturing, material recyclability, among others. Methods for product-specific disassembly planning have proven to greatly influence the nature of this research space. Many methods use graphical representations in the form of disassembly trees and/or networks to find feasible solutions with computational approaches. However, most of the published work has focused on assessing the disassemblability of simple modular products or high volume electronic products such as personal computer (PC) towers. Though important, these methods are often inapplicable to larger and more complex electrohydraulic mechanical systems such as automobiles, earth moving equipment and industrial machine tools due to problems associated with variations in product architecture, disassembly tasks and design methodologies. The work presented in this paper aims to apply a disassembly assessment technique by comparing a component's disassembly effort to a reward such as recycling value or energy recovery from recycling. First, the disassembly network is represented by a directed graph where weighted edges represent reward/cost. Next, an implementation of Dijkstra's algorithm is used to compute the optimal disassembly path that minimizes the sum of the edge weights. Lastly, the optimal disassembly paths for each individual reward are compared to discover the globally optimal disassembly scenario. This method is applied to a real-world case study of an underground mining drill rig with direct contributions from engineers involved in the development of the machine itself. Specific component recovery options are recommended based on the methodology and alternative design practices are suggested to improve product recyclability.

Prioritizing Design for Environment strategies using a stochastic Multi Criteria Decision Analysis

Ramanujan D., Bernstein W.Z., Choi J-K., Koho M,. Zhao f: & Ramani K. 2012.

ASME 2012.

Success in applying Design for Environment (DfE) depends on the selection of the most appropriate design strategy that reduces environmental impacts while still meeting business-related goals. One of the primary challenges in applying DfE within an industry setting is coupling implicit design knowledge, such as redesign/process constraints, with quantitative measures of environmental performance to enable informed decision making. For widespread adoption by the industry, the method should also address economic aspects of the DfE strategies under evaluation. This article describes a methodology for integrating life cycle assessment (LCA) and multi-criteria decision analysis (MCDA) in order to prioritize various levels of DfE strategies. The MCDA process is formulated so as to simultaneously improve the environmental and the business-related performance of a product. Moreover, in a realistic industry setting, the onus of decision making often rests with a group, rather than an individual decision maker (DM). While conducting independent evaluations, experts often do not perfectly agree and no individual expert can be considered representative of the ground truth. This necessitates a mechanism for assessing the variability in preferences among DMs. Therefore, a stochastic simulation module is integrated with the MCDA for analyzing variance and thus establishes the robustness of a decision. A sensitivity analysis is also incorporated to explore the dependence of decisions on specific input preferences. Finally, the article proceeds to apply the proposed methodology in a real-world case. The outlined framework was used by design experts from a leading mining equipment manufacturer based in Finland to prioritize DfE strategies for one of their surface drilling rigs; the results of which are presented.