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Abstract

Sustainable design is the idea of redesigning the world; enabling us to meet the needs of our current generation without compromising the ability of future generations to meet their own needs. Core to achieving sustainable design is the idea of lifecycle design. Lifecycle design looks at the design of a product throughout its entire lifecycle from concept through manufacturing, use and finally its end-of-life. Investigating the end-of-life of products is a whole new concept in product design that will continue to take on added importance in the near future.

This thesis investigates sustainable principles to see how they will steer the design of personal handheld consumer electronics. Can a sustainably produced product be competitive and innovative? What new insights will this view and life-cycle thinking have on the end results?

Acknowledgments

I would like to thank all the members of my committee. J, Gil, and Dale, have encouraged and guided me throughout the entire project. In my time as a student here, each of them has given me new insights that helped open my mind and develop my skills, giving me the courage to take on this project.

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PART I: OVERVIEW AND BACKGROUND

INTRODUCTION

The term sustainability is defined by the World Commission on Environment and Development as "meeting the needs of the present without compromising the ability of future generations to meet their own needs." It is crucial that we as a society begin to understand this concept and reshape our existence. We must reshape our industries to arrive at this definition.

We live in a world built by the industrial revolution. This revolution has done many great things to advance science and our society, but at great cost to our environment. We are in this industrial revolution today and are still locked into its belief system. This system was built under the assumption that our earth has an abundance of raw resources available for us to consume. And at the other end of the lifecycle, this system also assumes after we consume resources, there is an abundance of space to deposit our waste. We are beginning to realize that neither of these abundances actually exists. If we do not change the fundamental assumptions of our industrial society, we will begin to run out of resources and places to put our waste.

This is why we are entering the “Next Industrial Revolution”, what Paul Hawken calls “Natural Capitalism”. This Next Industrial Revolution will continue to further our science and society, but at no cost to our environment.

We need to find ways for our lifestyles and industries to live in harmony with our environment.

Cradle-to-cradle is a new approach to the Next Industrial Revolution in a way that aims to achieve complete harmony with natural systems. The originator of this theory, William McDonough, has reshaped the field of architecture by achieving sustainable building designs. McDonough has partnered with chemist Michael Braungart to write *Cradle-to-Cradle*. With the methodologies they develop, they aim to reshape the field of product design. These methodologies seek not to reduce environmental impacts of industry, but to completely eliminate them. They argue that ideas such as factor 10 or factor 20 reductions in pollutants are beneficial, but do not solve the inherent problem of waste production. Because these approaches still lie within the same thinking of our current system, any improvements only slow down waste production. The entire idea of waste needs to be eliminated.

To really change our industry requires new thoughts and new goals. Cradle-to-cradle has laid down such goals. I believe that the following principles can aid us in achieving true sustainable product development. The cradle-to-cradle principles were modeled on principles that are true in nature: 'waste equals food', 'respect for diversity', and 'use of solar income'.

The first principle, 'waste equals food', simply means that material waste should be the source of raw goods. Nature has no waste. All 'waste' in nature is used as a material resource by some other species. Put into context of an industrial system, all waste should be fed back into streams of production. Recycling should be done in such a manner to arrive at 100% of initial quality without degradation of the resource. Degradation of a resource, where after recycling it has lesser value, is what McDonough calls 'downcycling'. To avoid downcycling, McDonough introduces the idea of cyclical nutrients. Nutrients are either biological or technical. Biological nutrients are resources that can be used over and over again by returning them to the earth to biodegrade. Technical nutrients are man-made resources designed to suit technical needs. However, these technical nutrients must also be designed for use in a cycle, so that they may be used over and over again without a degradation of quality.

The consumer electronics industry is potentially one of the most harmful industries, and could greatly benefit from sustainable production. Consumer electronics is a very fast paced industry, continually striving to offer customers the latest and greatest technology each year. Many products are purchased only to be obsolete the next year. This leaves a great deal of obsolete electronics with little usability and nowhere to go. These products typically end up in the landfills. This problem is intensified by the fact that these electronics also contain a huge number of hazardous toxins, such as chromium, cadmium, and lead. If not properly disposed, all these toxins have the potential to run into the water table and cause a good deal of health and environmental hazards.

The mobile communications sector is of particular interest, where products are typically replaced once a year, with little to no thought placed on the end-of-life of the product. The goal of this thesis is to design a sustainable handheld communication device. The cradle-to-cradle approach will be applied as a filter to current best environmental design practices and current technology to arrive at a feasible solution for a device within the next 3 years.

EU LAW

Product manufacturers are seeking out new ways of integrating environmental policy in their business for a number of reasons: increasing consumer expectations, increasing resource efficiency, but the biggest motivator is new European Union Law. Simply described as extended producer responsibility (EPR), manufacturers are now held directly responsible for the waste they produce and the resources their operations consume.

In the United States, there has not been a huge need for change, as most of the effects of our wasteful living are spread out across a large area. However

Europe, with its lack of space and smaller pool of raw resources, has begun to feel the effects of our modern living.

Landfill space in Europe is quickly diminishing, so new laws were and are being developed to stem the flow of waste, and to see that this waste is free of hazardous substances. Finding space and finding proper disposal for all the waste generated is proving difficult and expensive for the Europeans.

Trash will now be classified as inert or hazardous. Trash will be checked to verify classification and see that it contains no recyclables. Also, biodegradable waste will be diverted to a composting heap. Fees will be charged to the producer based on classification. These fees are expected to rise yearly. It is now in a producer's interest to produce as little waste as possible.

EU laws apply directly to the producers of products and take a more pro-active part in environmental policy. "Precautionary principles, preventing actions, and 'polluter pays' principles are the present objectives of the [EU] Community policy. In waste management this means that waste generation should be reduced by improving product design. Reuse and materials recycling are favored, and more responsibility is assigned to producers" (Hundal 113).

In October 1997, the European Union came together to write the Treaty of Amsterdam. It addresses strengthening the economic environment of the collective union. A part of that treaty was an agreement to focus on sustainable development. The objectives stated are as follows: preserving, protecting, and improving the quality of the environment; protecting human health; prudent and rational utilization of natural resources; promoting measures at international level to deal with regional or worldwide environmental problems. Based on this treaty the EU has enacted a series of specific proposals that tackle a number of issues; for example, packaging and packaging waste, discarded batteries, end-of-life of vehicles, and waste of electrical and electronic equipment. All focus heavily on producer responsibility, and regulate a number of specific items that the producer must meet.

Waste of electrical and electronic equipment is seen as a particularly important focus. During 1998, 915,000 tons of electrical and electronic equipment waste (e-waste) was created. This accounts for only 4% of the municipal waste stream but is also one of the fastest growing types of waste, predicted to increase by 3-5% each year. Additionally, it is potentially a source of great harm because of the hazardous substances it often contains, such as lead, cadmium, mercury and hexavalent chromium. If these substances are not carefully regulated, they have the potential to enter the water table and result in massive health issues. (Faversham House Group Ltd)

In July 1999, the EU completed the Directive on End-of-Life Electronic Equipment. It states the members shall:

- Promote the design and production of electrical and electronic equipment for repair, upgradeability, reuse, dismantling, and recycling, and particularly to increase the use of recyclable materials
- Ensure that all ISO regulations are followed regarding identification of recyclable plastics
- Ensure that the use of lead, mercury, cadmium, and hexavalent chromium, and halogenated flame retardants are phased out by January 1, 2004
- Ensure that collection systems are set up for products at end of life from last holders and distributors
- Ensure that the costs for collection, treatment, recovery, and environmentally sound disposal of waste electronics are borne by the producers of those products
- Ensure that no later then January 1, 2004 the following reuse and recycling targets (% by weight) are attained by producers: large household appliances, 90%; small household appliances, 70%; radio, television, electroacoustics, 70%; gas discharge lamps, 90%; toys, 70%; electrical and electronic tools, 70%; equipment containing cathode ray tube, 70%

WEEE AND ROHS

The Directive resulted in passing specific laws governing e-waste for all of the European Community. In February 2003, two new laws were announced regarding the electronics industry and banning harmful electronic materials. The first of these laws is known as the Restriction of Hazardous Substances (RoHS). This law targets commonly used substances known to be hazardous. Laws soon to take effect specify even more materials that will either be banned or heavily fined. The European Association for Standardizing Information and Communication Systems (ECMA) put together the following list of materials that should not be used: Laws will take effect 2006 with penalties starting in 2008.

- Asbestos
- Cadmium (Nickel-Cadmium batteries)
- CFCs (chlorofluorocarbons) and HCFCs (Hydrochlorofluorocarbons)
- Chloroparaffins
- Lead
- Mercury
- PCBs (polychlorobiphenyles) or PCTs (polychlorotriphenyles)
- Hexavalent chromium
- Polybrominated biphenyls

The second law put into effect is known as the Waste of Electrical and Electronic Equipment (WEEE). This law's goal is to reduce waste of electronic equipment and encourage recycling of discarded products. By August 2005, consumers will be able to return products to the producer free of charge, where they can be properly disposed of or recycled. By December 2006, producers will be required to achieve targeted recovery and recycling goals:

> The European Commission has adopted a proposal for a Directive on Waste Electrical and Electronic Equipment (WEEE) and a proposal for a Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment... Increased recycling of electrical and electronic equipment, in accordance with the requirements of the proposal for a WEEE Directive, will limit the total quantity of waste going to final disposal. Producers will be responsible for taking back and recycling electrical and electronic equipment. This will provide incentives to design electrical and electronic equipment in an environmentally more efficient way, which takes waste management aspects fully into account. Consumers will be able to return their equipment free of charge. In order to prevent the

> generation of hazardous waste, the proposal for a Directive on the restriction of the use of certain hazardous substances requires the substitution of various heavy metals and brominated flame retardants in new electrical and electronic equipment from 1 January 2008 onwards (EUROPA).

"After 10 years of debate the EU directives Waste Electronic and Electrical Equipment (WEEE), and Restricting the use of Hazardous Substances (RoHS) are becoming a reality. The impact on the way manufacturers design, produce and dispose of their products will be huge" (Electroversal).

The EU has gone into far greater detail, proactively regulating pollution prevention compared to the at-the-pipe legislation of the United States. This will soon have a huge effect in the US because it applies not only to products produced there, but also to most products sold there as well. Because of our global economy, these EU policies are directly impacting US producers, too. The entire industry and way of doing business is changing to meet the requirements of these new laws.

Many developers are scrambling to learn as much as possible about these laws, how they affect them, and how best to change their operations in preparation. There is a huge need for corporate and development training on these issues. One organization, the South East Environmental Business Association (SEEBA) [of the U.K.] is offering this service. SEEBA is a part of the Center for Sustainable Design, directed by Martin Charter. They produced the following chart:

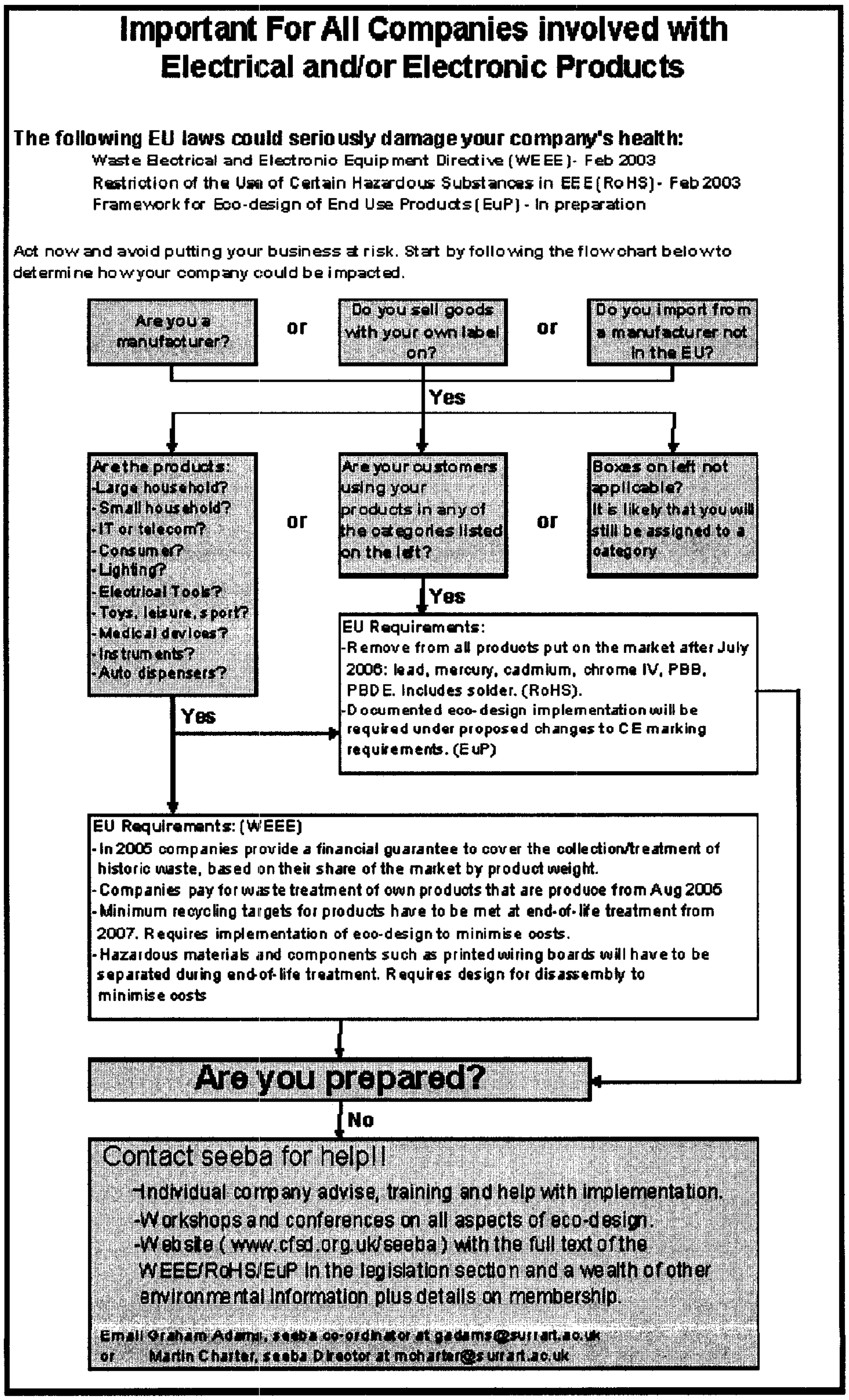


Figure 1: SEEBA EU law preparedness flow chart, from Martin Charter, Center for Sustainable Design. May 2002 <http://www.cfsd.org.uk/seeba/>

PART II: RESEARCH AND METHODOLOGIES

ENVIRONMENTAL MANAGEMENT SYSTEMS

Companies and organizations need to effectively deal with these upcoming laws. For this, they are developing and implementing Environmental Management Systems, or EMS. An EMS is a system that companies or organizations can implement that enables them to ensure that they have a grip on all facets of environmental issues.

In addition to meeting the requirements of upcoming EU laws, there are a host of other elements convincing companies to implement an EMS. These include: minimizing the cost of wasted energy and materials, getting ahead of competition, marketing as an eco-conscious company, satisfying public, employee, and shareholder's environmental concerns.

In order to minimize wasted materials and energy, it is important to locate the flow of all materials and energies involved in the production of a product. The ultimate goal is to know what when and where waste occurs, what possible legislation and/or cost is concerned, and to fix any problems. An EMS facilitates this process. It involves monitoring environmental effects due to production, ensuring that all necessary data is properly gathered, and making sure plans for development and improvement are in place.

The process of implementing an EMS relies heavily on accurate environmental data obtained from all associated companies or industries involved in the production of any one product. Because of the amount of data exchanged and the necessary procedures involved, EMS needs to be standardized.

Based on this need, the International Standards Organization (ISO), helped develop a standardized EMS system in the early 1990s. This standard is known as the ISO 14000 series.

ISO 14000

ISO develops standards for a variety of measurements and management systems. These standards ensure the compatibility of products and services of all types. People come in contact with them and rely on them in countless ways. Some examples include standardized units of length, weight, time, shipping and transportation, even computer file exchange formats. For instance, ensuring that what everyone refers to as a meter is all the same.

The two major management systems ISO has standardized are ISO 9000 and ISO 14000. The ISO 9000 standard is a quality management system. It can be applied by any industry to insure that the product or service they deliver is of high quality with a minimal amount of defect. This means improved efficiency and less waste for industry. In the product industry, there is a good deal of science established to ensure a low number of defective parts. There is a lot of specific data that needs to be obtained in very specific ways to ensure that the system works correctly. This system and data is key to the management system that ISO 9000 specifies. Without these standards and the work of ISO, this system would be impossible to operate.

ISO 14000 is similar to ISO 9000, but deals with environmental management rather then quality management. ISO 14000, launched in 1996, is a series of international voluntary environmental management standards. "ISO Standard 14000 defines requirements on an EMS. It is intended to enable companies to bring their EMS in line with other internal policies and requirements. The standard is meant to be applicable to any company regardless of its size and of geographic, cultural and social conditions. Its overriding goal is to promote environmental protection and to achieve environmental and economic goals" (Econcept Glossary). "It is a voluntary system, and does not translate into a company being environmentally benign, but does allow the company to become responsible, and mark a path to improvement" (Goldberg 229). Its main function is to provide encouragement and be flexible enough for a variety of organizations. It does not set rigid environmental requirements.

ISO 14000 insists the following elements must be in place for a company to obtain certification:

1. EMS System - Proof that an EMS is in place and operating, all set up by top management (knowledge of requirements by law, statement of

policy, setting of goals, carrying out management through company including training and definition of individual responsibilities and system to run it)
2. LCA data - Ability and practice to obtain data of the full environmental effects and impacts (from cradle to grave: raw materials, production, use, and end-of-life) that a company and its suppliers have in the development of any current or planned product
3. Continuous improvement - Show commitment to plans and goals and to continuous improvement.

Certification is done by an accredited agency. Initial certification demands these requirements can be met and that an effective system is in place. Furthermore, certification must be renewed every 6 months by ensuring goals are continuing to be met, and that there is continuous improvement.

The ISO 14000 standard is broken down into individual elements of the series. Elements relate to various aspects of planning, acting, and checking, but all contribute to full implementation of an EMS.

14001- 1401X EMS	Implementation
14020 series	Labels and declarations
14030 series	Environmental performance evaluation
14040 series	LCA
14050	Definitions and vocabulary
14062	DfE principles
14063	Environmental performance communications
19011	Auditing and certification of ISO 14000

The following is an example of how ISO14001 improves the environmental practice of a company.

The best way to look at an environmental policy is to think in term of conservation of resources. In other words, you want to waste as little as possible. The result is less environmental impact and better profitability. For example, if your plastic injection machine wastes 100 pounds of resin during set up, you have created a considerable loss. The resin has to either be reprocessed (thus using up more energy) or disposed of. However, if the set-up method is optimized so that only a few pounds of resin are wasted, then energy is conserved and it costs less for the production run (Isogroup).

The one major key of ISO 14000 is finding data of the precise ingredients and impacts of any given product or service. This is known as LCA, or Life Cycle Assessment. This involves a tremendous amount of specified data, obtained in specified methods. This is why it takes an international system like ISO to implement.

LCA

Life Cycle Assessment, sometimes referred to as Life Cycle Analysis, is a tool to measure environmental impact of a product, process, or service, and then evaluate opportunities for improvements. More specifically, it is a way to look at the life cycle of a product and determine what materials and energy it contains, throughout its entire life. LCA also allows opportunities for environmental improvements by comparing possible options on a level playing field.

"An LCA can show the major environmental problems of a material, product or process. The act of doing the assessment builds awareness about environmental impacts and focuses improvement efforts" (Hundal 27).

When someone asks, “paper or plastic?” what should you answer if you wanted to be the most environmentally friendly? The only true way to answer would be to conduct a full LCA on both the paper bag and the plastic bag. This would require having a full list of elements that are embedded in each, as well as how much embodied energy they contain. Also, what wastes were emitted at each process step along the way? How about the energy it took to transport the materials along the way, and the energy and impacts of those transportation methods? And then, what will happen to the bag at the end of its life? Will you recycle it or throw it in the trash? What transportation will it further undergo? If trashed, what environmental costs will occur? Will it be incinerated? If recycled, what benefits will it offer? Only once all these questions (and likely more) are answered, quantified, and looked at on a level playing field, will you be able to honestly answer the original question. With all the companies and organizations involved, it’s no wonder it takes an international standardized system to get this done.

What is a lifecycle? The lifecycle of a product begins with the acquisition of raw materials and includes processing of bulk materials, manufacture, transportation, use, retirement, disassembly and disposal of residuals produced in each stage. This typically encompasses life from ‘Cradle to Grave’.

The first LCA was conducted in 1969 by Bill Franklin and Harry E. Teastley, Jr. It was for Coca-Cola, to determine whether plastic or glass bottles had a lower environmental impact. It took into account everything from raw materials to waste disposed. It also analyzed various end-of-life options, such as landfill or recycling. It determined to much surprise that plastic was a better choice.

The concept of conducting an LCA was further developed in the mid 1970s as a result of the energy crisis. This alerted people to the fact that our natural resources are indeed of a finite supply. Technologists attempted to design products so they would consume less energy, but needed a way to quantify energy and resource requirements. This developed LCA to the science it is today.

According to ISO, there are four parts to conducting an LCA. They are as follows:

ISO 14040: Definition of the goal and scope
ISO 14041: Life cycle inventory (LCI) analysis
ISO 14042: Life cycle impact assessment
ISO 14043: Life cycle interpretation

The first step to an LCA is to define the goal and scope. This includes drawing a system boundary around the parts of the system the investigation will include. Once the system boundary is laid out, the next step is to look within the boundary of the system and to individually analyze all various elements (mass and energy) and plot paths of flow. This includes material and energy used at each process and all waste or pollutants.

The following graphic depicts what the overall goals of an LCA are when looking at the life cycle of a product:

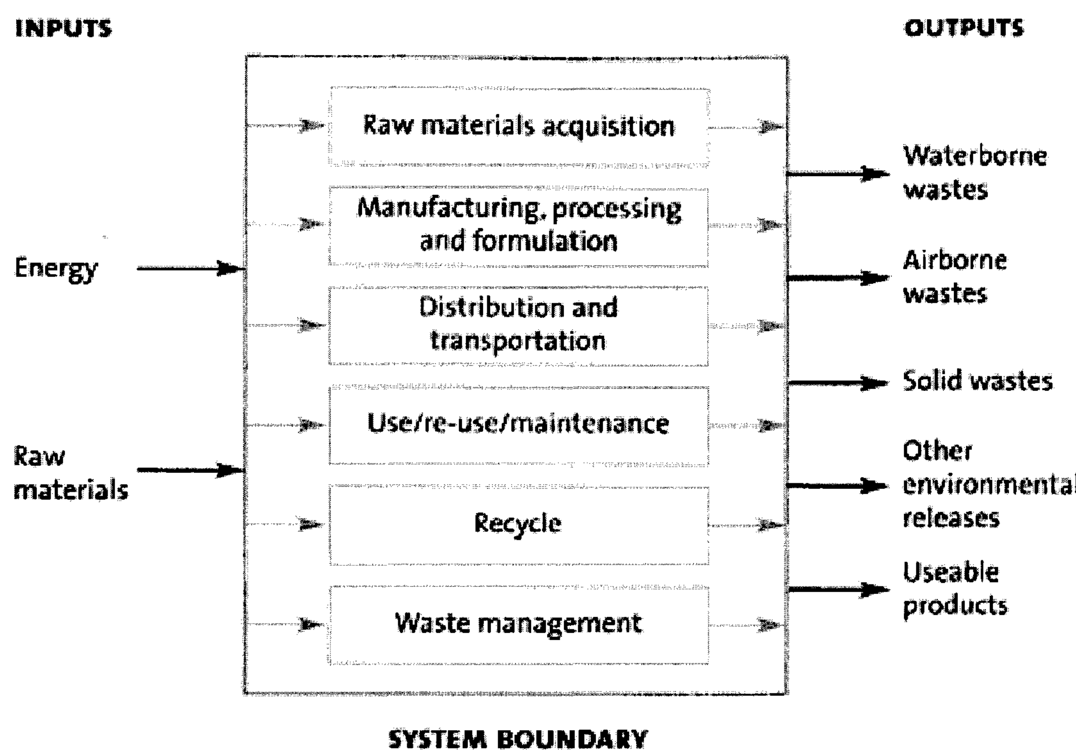
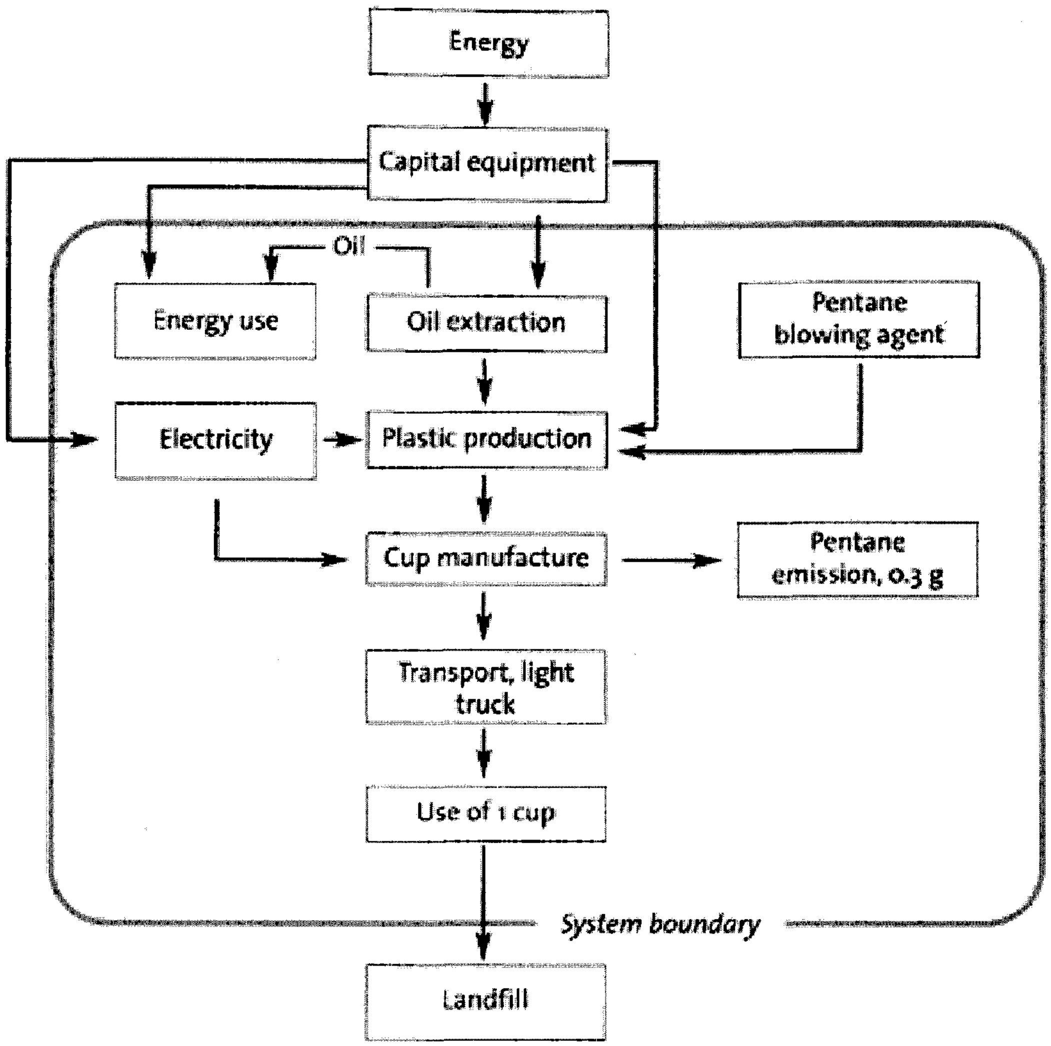


Figure 2: Product system from a life-cycle perspective, from Helen Lewis and John Gertsakis, Design + Environment: a Global Guide to Designing Greener Goods (Sheffield: Greenleaf, 2001) 42.

The following is an example of the LCA of a polystyrene cup. The next step is to look within the boundary and determine all the individual components and the flow paths of matter and energy.



Goal: to determine the main environmental impacts of the polystyrene cup, and the stages of the life-cycle where they occur.

***Scope** (Australian situation):* include all material production stages, transport and use, excluding data on capital equipment and final disposal of cup.

Figure 3: Life-cycle assessment: example of the goal and scope for a polystyrene cup,
from Helen Lewis and John Gertsakis, Design + Environment: a Global Guide to Designing Greener Goods (Sheffield: Greenleaf, 2001) 44.

The second stage of an LCA is to do a Life Cycle Inventory (LCI) Analysis. All the technical data is gathered to find energy and raw materials. Atmospheric emissions, waterborne emissions, solid wastes, and other releases of the product/process/activity life cycle are quantified. Here are the results from the polystyrene cup LCA

Raw materials

Substance	*Unit*	
Bauxite (ore)	mg	35.2
Clay	µg	440
Coal	g	2.39
Crude oil	g	26.3
Iron (ore)	mg	9.94
Limestone rock	mg	19.8
Natural gas	dm^3	22.4
Rock salt	mg	26.4
Water	cm^3	183

Airborne emissions

Substance	*Unit*	
Aldehydes	ng	45.3
Aluminium	µg	6.95
Ammonia	µg	2.09
Carbon dioxide (CO_2)	g	77.4
Carbon monoxide (CO)	mg	189
Copper	µg	3.49
Dioxin	pg	0.973
Dust	mg	124
Ethanol	ng	695
Ethene	µg	27.8
Ethyl benzene	µg	13.9
Formaldehyde	µg	2.78
Halon-1301	g	2.09
Hydrocarbons (C_xH_y)	mg	509
Iron	µg	6.95
Methane	mg	74.9
Methane	mg	2.74
Methanol	µg	1.39
Magnesium	µg	2.09
Nickel	µg	13.9
Nitrogen oxides:		
N_2O	µg	286
NO_2	mg	2.87
NO_x	g	1.02
PAH[a]	µg	1.32
Pentane	g	1.45
Propane	µg	556
Propene	µg	27.8
Radioactive substances	Bq	792
Silicates	µg	13.9
Soot	kg	32.8
Sulphide (H_2S)	µg	111
Sulphur oxides (SO_x)	g	3.25
Toluene	µg	195
Vanadium	µg	55.6
VOC[b]	mg	57.7
Zinc	µg	8.34

Waterborne emissions

Substance	*Unit*	
Acid[c]	µg	1.76
Aluminium	µg	243
Ammonia	mg	9.45
Arsenic	ng	695
Barium	µg	973
Benzene	µg	50.7
BOD[d]	mg	2.68
Boron	µg	13.9
Calcium	mg	13.4
Chlorine (Cl_2)	mg	2.2
Chlorine ions (Cl^-)	mg	207
COD[e]	mg	60.5
Copper	µg	2.09
Cyanide	µg	2.09
Dissolved organics	mg	7.04
Dissolved solids	mg	8.68
Hydrocarbons (C_xH_y)	mg	15.3
Lead	µg	2.78
Magnesium	µg	799
Manganese	µg	27.8
Molybdenum	ng	695
Nickel	µg	2.09
Nitrogen	mg	1.26
As nitrate	µg	250
Total	µg	4.7
PAH[a]	µg	4.87
Phenol	µg	48.7
Phosphate	µg	20.9
Radioactive substances	Bq	7.3
Sodium	mg	126
Sulphate	mg	8.2
Suspended solids	mg	50.3

Solid emissions

Substance	*Unit*	
Chemical waste	mg	154
Diesel oil sludge	µg	308
Dust[f]	mg	21.3
Final waste (inert)	µg	577
Industrial waste	mg	9.5
Inorganic (general)	kg	0.0423
Mineral waste	mg	242
Product waste (active)	kg	0.00077
Slag	mg	76.6

a Polycyclic aromatic hydrocarbons
b Volatile organic compounds, excluding methane
c As H^+
d Biochemical oxygen demand
e Chemical oxygen demand
f Not specified

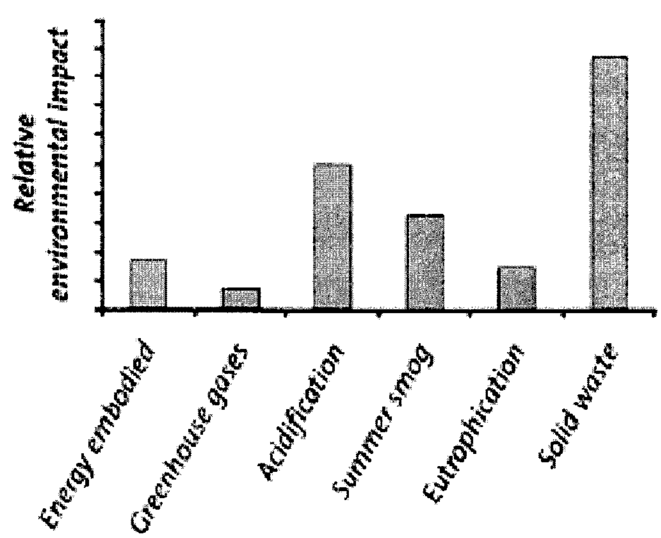
Note that this data is for illustrative purposes only and should not be taken as actual data for a polystyrene cup. The large number of inventory entries provide little useful information for decision-making. The next stage of the LCA groups the data into indicators or 'impact categories'.

Figure 4: Life-cycle assessment: example of Inventory results for a polystyrene cup,
from Helen Lewis and John Gertsakis, Design + Environment: a Global Guide to Designing Greener Goods (Sheffield: Greenleaf, 2001) 45.

A tremendous amount of data is collected just for a single cup.

The third stage in an LCA is to analyze the collected data, and attempt to draw connections to potential impacts. This is called a Life Cycle Impact Assessment, and is not a straightforward exercise. Many chemicals' impacts remain unknown. In general, links are drawn to three various types of impact: global, regional, and local. Global impacts include ozone depletion, global warming, and resource depletion. Regional impacts include acidification and smog. Local impacts include human heath, terrestrial toxicity, aquatic toxicity and land use.

The results of the polystyrene cup are shown:



These results have been normalised (compared to a reference value such as total yearly impact for each impact). Categories can also be weighted and summed together to form an eco-indicator.

Figure 5: Impact assessment results,
from Helen Lewis and John Gertsakis, Design + Environment: a Global Guide to Designing Greener Goods (Sheffield: Greenleaf, 2001) 46.

In the case of the cup, solid waste is the biggest concern. Apart from the cup being discarded, there is also a major amount of scrap generated during the molding process. The acidification is a result of the energy produced at the power plant. Finally, smog results from off-gassing in the plastic's production (Lewis 47).

There is lots of room for research in linking chemicals to specific environmental impacts. However, currently it is safely assumed that if a hazardous waste is emitted, the best plan is to reduce it.

Life Cycle Interpretation is the final stage of conducting an LCA. At this stage, the results are interpreted. The major concerns are prioritized, for opportunities to make the biggest impacts. Other LCAs on system options are conducted and compared. At this stage, plans can be formulated for improving the product, with data available to back up decisions.

LCA in Product Design

The results of an LCA are an effective tool that points out key items to target for improvement and redesign. A designer can use these items to ensure future products are more environmentally friendly.

In looking at the design of a sofa, LCA pointed out materials selection is the most important factor. Next in importance are paints and finishes. The last is transportation. Designers should thoroughly analyze materials and finishes for impact. Designs should minimize transportation distance and shipping volume (Burall 131-153).

The only way to improve our current system of production is to know exactly how harmful it is. Only when all the effects are known can we effectively target improvement and measure the success of innovation. Conducting an LCA is currently the only way we can truly evaluate the environmental impact of the products we produce.

Because of the extensive amount of data needed to conduct an LCA, all suppliers in connection with the product need to be certified to use the ISO 14000 system. This way, all the suppliers of a product, and all their suppliers, will have the data needed to produce an accurate LCA.

Recently, Volvo Car Corporation accomplished just this. They required all their suppliers to get certified if they wished to continue to do business. Those who did not were no longer used. As a result of having 100% of their suppliers 1S0 14000 certified, they are able to obtain accurate environmental information. This allows them to continually improve their products and processes. This is the current trend in Europe, as most suppliers who want to continue to do business must be ISO 14000 certified.

However, for every company to conduct a full LCA on every product, nearly every supplier and company in the world would have to be certified in the ISO 14000 system. In the United States there is no push from customers to get ISO certification, and consequently few companies or suppliers have it. As a result full LCAs are not currently feasible in the US. Full LCAs are the only tool to truly understand the environmental impacts of industry. There are other tools, however, that can do a quick and rough estimate of LCA, and still other tools that help evaluate designs and other areas.

ECODESIGN TOOLS

Streamlined LCA + Other Environmental tools

Although a full life cycle analysis is the best option to truly make a product environmentally friendly, it is often not realistically possible. Barriers to a full LCA include suppliers and companies (especially in the US and most Asian countries) not having ISO certification, and a full LCA is often too costly and too time/resource-intensive for most product development outfits. The need for a quick effective substitution for a full LCA has been noted for years, and many options exist. Alternatives are known as 'Streamline LCA Systems' and other EcoDesign tools.

A streamlined LCA is much quicker and cost effective than a full LCA. However, the results are at best a rough approximation of the actual system.

But a streamline LCA enables designers to identify major environmental impacts and make fairly informed decisions about materials and processes that should be chosen for production.

There are a variety of tools that designers can use to quickly compare ideas, get a picture of environmental impact, and test financial feasibility. These are known as EcoDesign tools. Streamline LCAs are just part of the variety of tools available. How to do EcoDesign?, breaks the available tools into four categories:

1. Analysis of environmental strengths and weaknesses
2. Setting priorities and selecting the most important potential improvements.
3. Implementation: providing assistance for design, brainstorming and specifying the details of ideas
4. Coordination with other important criteria: cost-benefit analysis, economic feasibility studies

Each tool available has different applications of subject or what design phase to use them in. Breaking them down into the likely order they would be used if conducting a full redesign on an existing product, a designer comes up with the following.

Analysis of environmental strengths and weaknesses

This section mainly consists of the LCA tools, Full LCA, Streamline LCA, various software and number systems. It is best to use this set of tools first. Use them to analyze the existing product/production/system to find all the environmental impacts. They are also good to use to compare a set of options, such as material choices or production techniques. Be sure to make comparisons on a level playing field to get valid results.

Most streamline LCAs are essentially pre-gathered LCA data for particular materials or processes. Most streamline LCAs are developed on data of a certain region. For example, the Eco-Indicator99 model was developed by the PRé Consultants of the Netherlands (www.pre.nl), based on data obtained in Europe. If this LCA is applied to processes or materials out of that region, it is not accurate. However, it will probably serve as a fairly good indicator, and the loss of accuracy is probably worth the benefits of convenience and cost.

Number Systems (aka Proxy Indicators)

Streamline LCA is really just an equation of a predetermined LCA based on the impacts of various materials and processes. Single number values are assigned to various products, processes or materials to rate their environmental impact. A user can simply input various material choices and processes and arrive at a final single number. Following is list of popular systems:

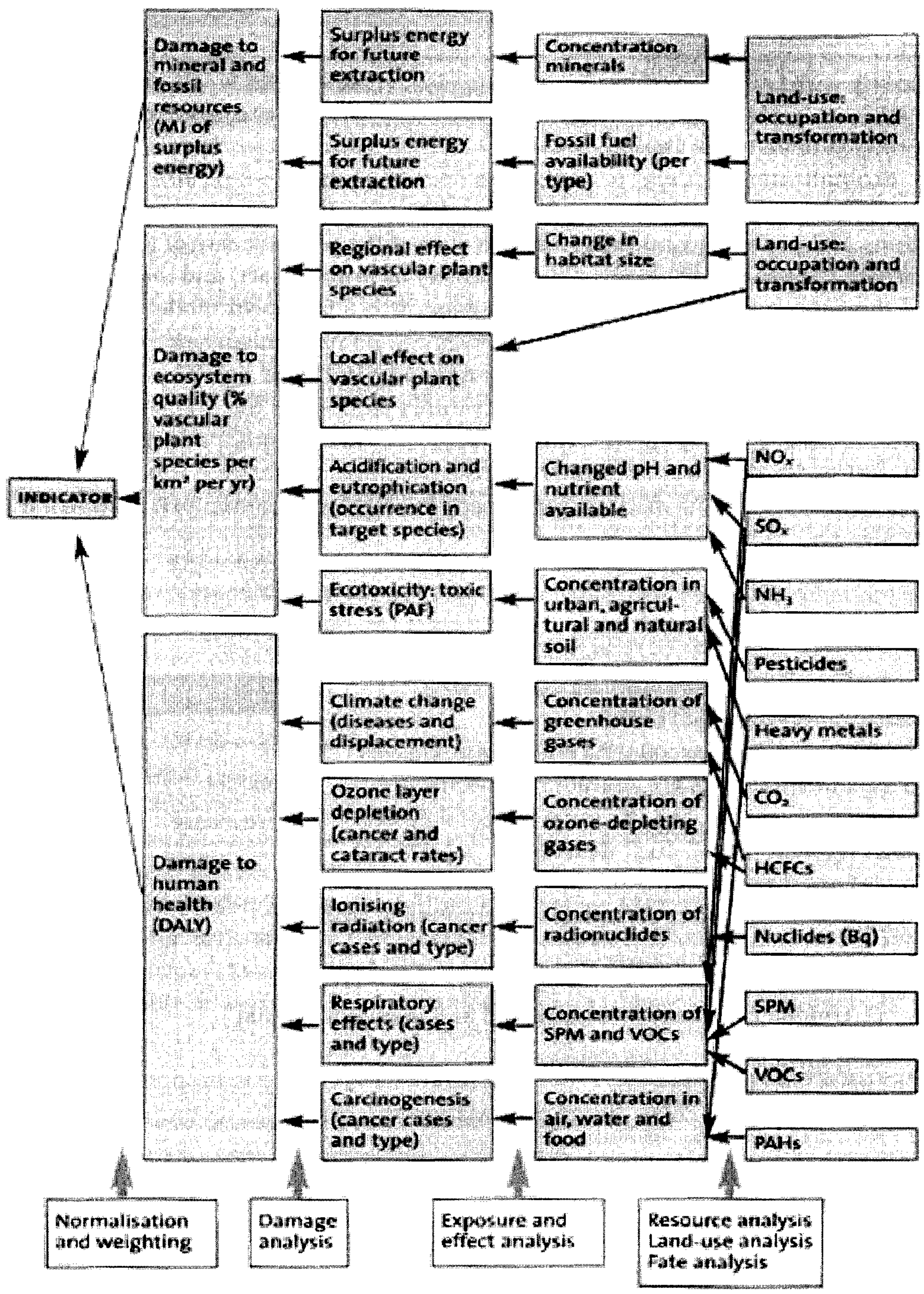
Embodied Energy
MIPS – Material Input per unit of service
Eco Footprints
Eco Indicators such as Eco Points, EPS, and finally Eco-indicator'95 and Eco-indicatior'99

All systems work from a highly built-up database containing common materials and processes. Most systems work directly with or are available as software.

Eco-indicator 99 is probably simplest and is most widely used by designers. Developed by PRé Consultants with the Dutch government. Eco-indicator '99 draws upon the IDEMAT database.

IDEMAT is a computer database of over 365 materials developed by the Environmental Product Development of the faculty of Industrial Design Engineering at the Delft University of Technology. It provides technical information about materials and processes in words, numbers and graphics, and puts emphasis on environmental information. The program was developed to be used by students of technically oriented academic disciplines like Industrial Design, Mechanical Engineering, Civil Engineering, Materials Science, and Aerospace Engineering (Lewis).

Below is a graphic depicting how Eco-Indicator 95 is calculated. For every material, an LCA is conducted. The impacts are found and compiled into one number each, for global, regional and local impact. These three numbers are factored into one final number for the system (Lewis 58):



Bq, bequerels; CO_2, carbon dioxide; DALY, disability adjusted life years; HCFCs, hydrofluorocarbons; MJ, megajoules; NH_3, ammonia; NO_x, nitrogen oxides; PAF, percentage affected fraction (of species of vascular plants); PAHs, polycyclic aromatic hydrocarbons; SO_x, sulphur oxides; SPM, suspended particulate matter; VOCs, volatile organic compounds

Figure 6: Eco-indicator 99 model, from Helen Lewis and John Gertsakis, Design + Environment: a Global Guide to Designing Greener Goods (Sheffield: Greenleaf, 2001) 58.

Many of the LCA systems are integrated into software. The software systems quickly offer assessments. They often specialize in a particular industry or market. The software falls into three categories: LCA modeling tools, product assessment models, and process assessment models. The information from Lewis shows tools listed in order of decreasing effectiveness and insight as well as increased simplicity and ease of use:

LCA modeling tools- allows users to fully assess the entire impact of a system in a step-by-step way. They often draw upon detailed data, but also allow users to input their own data

- SimaPro
- TEAM
- GaBi
- Umberto
- PEMS
- Boustead
- TRACI – via EPA
- Eco Manager
- LCAD

Product assessment models- these are generally thought of as simplified LCA tools. They also draw upon detailed data and often do not allow the users to add their own data. But they generally give a simplified single number score to the various materials, processes and energies found in the system.

- Eco-It
- EcoScan
- Idemat
- EcoPro
- REPAQ

Process Assessment models- These are generally thought to be the simplest tools, and simply alert the users to alternative cleaner production models, and design improvements.

- P2Edge
- LCAiT

Setting priorities and selecting the most important potential improvements. These tools are used once an LCA is completed and major environmental impacts are located. These tools allow impacts to be examined and prioritized. This way, a designer can focus efforts to make the biggest improvements. A full LCA has this feature built in, as do most streamline LCA systems, such as those covered in the previous section.

Implementation: providing assistance for design, brainstorming and specifying the details of ideas. This set of tools is used during the actual design phase of a project. Some examples include checklists, spider diagrams, rules of thumb. The main focus is to keep all the aspects of good EcoDesign in the front of the mind of the designers. They are not heavy in analysis or technical details. This is why implementation tools are best for industrial and product designers. They assist good brainstorming and identifying key goals to hit. Specific examples include the Eco-Lids Wheel, and DfE principles.

The concept of the spider diagram is simply that you make a polar diagram, or web diagram, typically with eight axes. On each of the spokes you make a category of some aspect of the design. Then you rate designs on how environmentally friendly they are, by plotting the scores on each spoke of the wheel. By looking at the difference between two areas, the two designs can be compared. Sony is said to have developed the first one, using the following aspects for spokes: hazardous material/wastes, time for dismantling, materials/product labeling, recycling rate, input of recycled materials, reduction of material value, energy use in production, and total energy use (Tischner 91).

There are also checklists. These quickly point out various details that might be easily missed or overall goals to reach. Some examples from How to do EcoDesign?, include: ABC-analysis, Eco-Estimator, Phillips Fast Five, WEEE directive checklist.

Of all the systems, one of the most effective is the Eco-LiDs (Eco Lifecycle Design Strategy) wheel diagram. It was developed by Carolien van Hemel and Han Brezets for the UNEP EcoDesign Manual. It is a spider diagram with eight axes. The following aspects are used for spokes: new concept development, material/component selection, optimization of production processes, reduction of material/component usage, optimized distribution system, reduction of impact during use, optimization of initial lifetime, and end-of-life management. For speed and effectiveness, it is tough to beat. At the early stages involved with industrial design, so many unknowns exist, so it is best to aim for a general policy of sustainable design. This includes hitting most of the key principles, such as recyclable materials, energy use, recovery systems throughout the product's entire life cycle. The specifics that a full LCA or streamline LCA give are great for fine tuning designs but don't apply well to conceptual design.

Eco-LIDS Wheel: Ecodesign a promising approach,
Source: UNEP/Delft University, Brezet/van Hemel

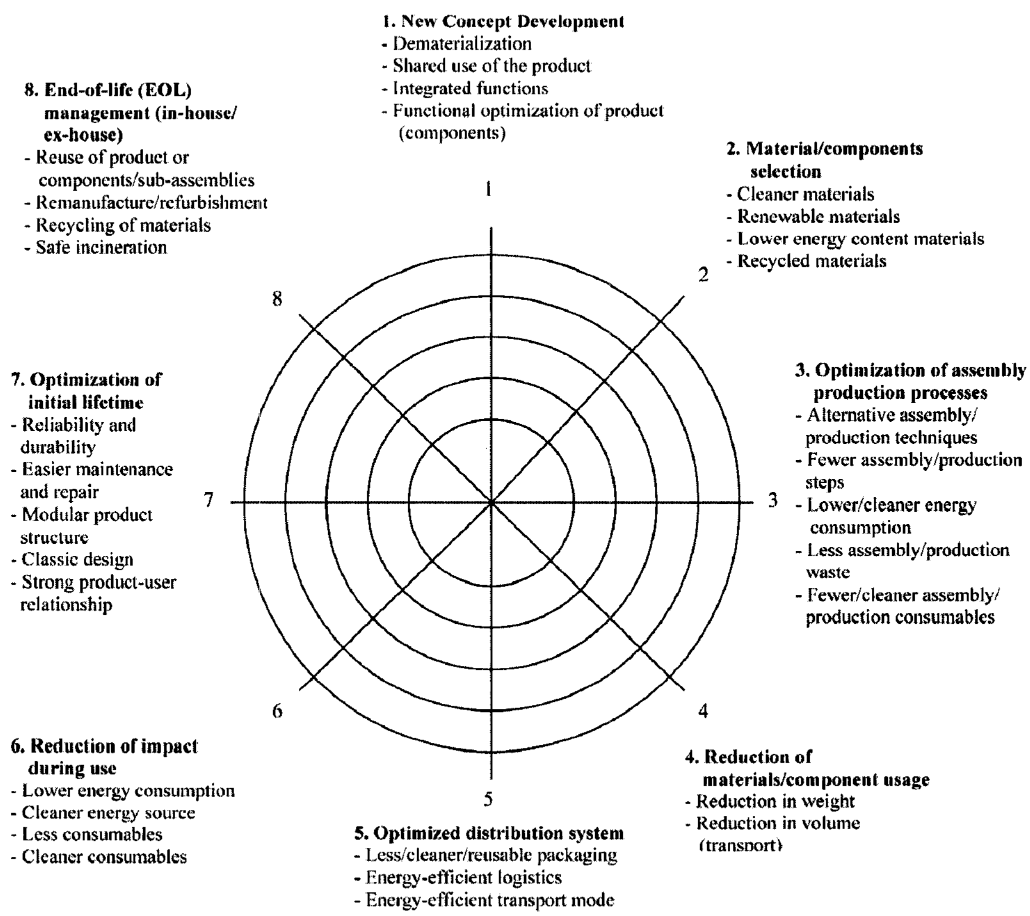


Figure 7: EcoLIDS Wheel , from Ursula Tischner, ed., How to do EcoDesign?: a Guide for Environmentally and Economically Sound Design. (Frankfurt am Main: Verlag form, 2000) 97.

Coordination with other important criteria: cost-benefit analysis, economic feasibility studies. Finally, this last set of tools comes in most handy to do detailed final analysis of the product and system. This includes financial feasibility, marketing, technical feasibility, and quality. Most of these systems are already in place in many organizations. They can be adapted to highlight environmental aspects. Examples include cost benefit analysis, house of quality, and evaluation matrices. These tools typically do not affect the design ideation phase.

ECODESIGN

Designing more environmentally friendly products is now necessary due to up-coming laws. Designers now have systems available to find the biggest impacts on the environment and trace them back to the product. How can product designers use this data and the concept of 'EcoDesign' to design better products for tomorrow?

The key to effective eco-design is understanding the concept of the product's lifecycle. Products must now be designed with full consideration of the entire lifecycle. This is what is known as 'lifecycle thinking'. 'Lifecycle thinking' takes into account all the environmental impacts that occur in the complete lifecycle of a product. Product designers are already very good at reducing environmental impacts at the front end of the lifecycle; from resource acquisition, production, distribution, and use. However, end-of-life is rarely a consideration in product design. The complete lifecycle includes mining and materials production, production of components and subassemblies, assembly of products, and the reuse and discarding of products (ECOLIFE, EcoDesign Guide). All of these categories must be simultaneously looked at and compromises made in order to arrive at the best overall design solution.

EcoDesign means environmentally conscious product development and design through the ideas of lifecycle thinking. As seen in the below graphic, EcoDesign is product design with additional environmental issues taken into account. It differs from sustainable design, which additionally takes into account social and ethical concerns. The entire system is considered sustainable development. Tischner says, "The term EcoDesign directly expresses the fact that **Eco**logy and **Eco**nomy must be joined inseparably by means of good **design** in EcoDesign procedures. Put in brief: EcoDesign leads to products, systems, infrastructure and services, which require a minimum of resources, energy and land area to provide the desired benefit in the best possible way while at the same time minimizing pollutant emissions and waste arising over the entire lifecycle of the product."

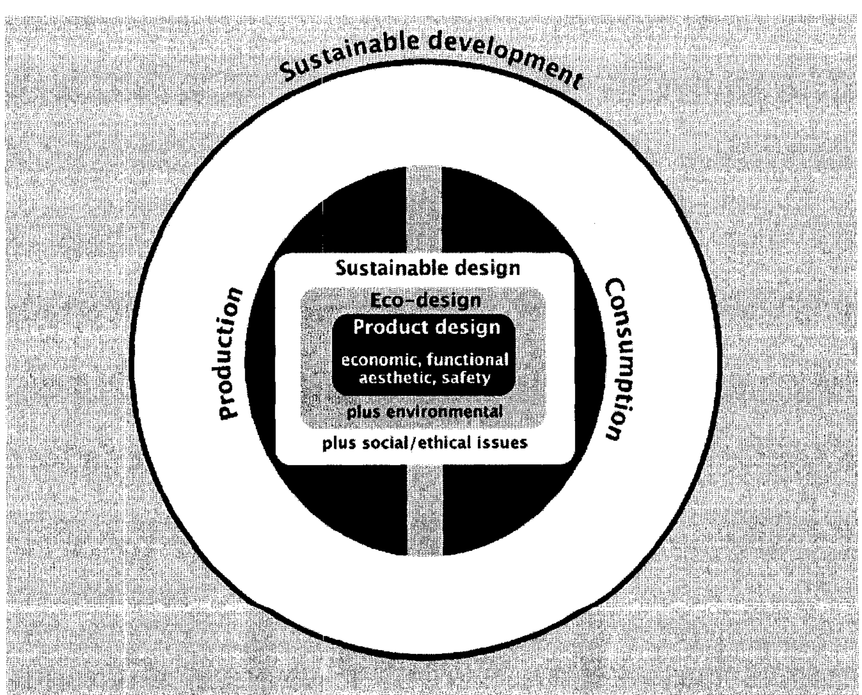


Figure 8: The Relationship Between Eco-design and Sustainable Development, from Ursula Tischner, ed., How to do EcoDesign?: a Guide for Environmentally and Economically Sound Design. (Frankfurt am Main: Verlag form, 2000) 16.

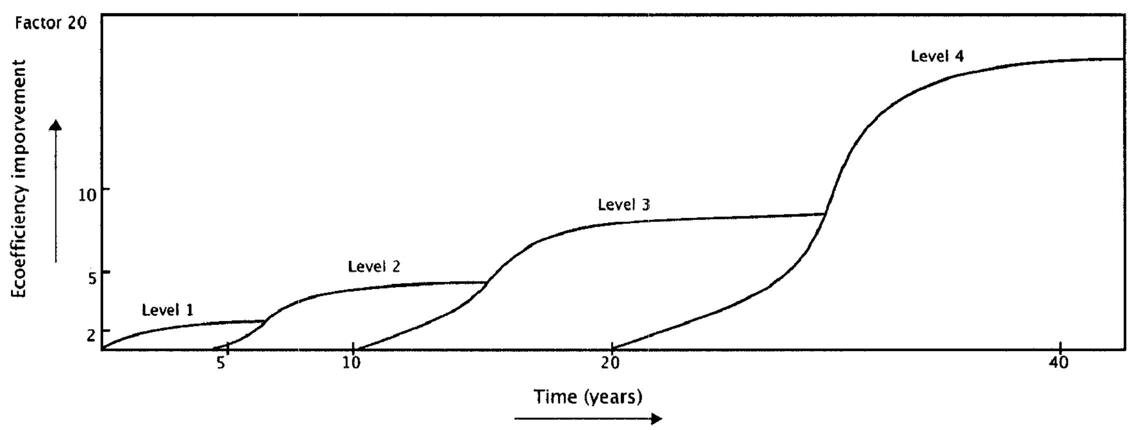
Why do it? The following is a list of reasons for why EcoDesign is attractive.

This list is taken from How to do EcoDesign?:

Why do EcoDesign?

- "EcoDesign is doable." There are many tools and literature established.
- "EcoDesign saves cost." Reduce material, easier quicker assembly due to design for disassembly methods, a reduction in upcoming liability risks, and recycling can bring back revenue for material at the product's end of life.
- "EcoDesign permits new solutions." This fresh start in the design process leads to new innovative ideas
- "EcoDesign provides opportunities for value creation in various lifecycle phases." First, the product can be reused at the end of its service, modular assembly design means that components can be taken out and re-used, and finally, raw materials can be recycled at end of life.
- "EcoDesign is good for marketing." This can be used to build a better corporate image.
- "EcoDesign enhances product quality." Design products as a service; reuse and recycling means that they are more durable, and repairable.
- "EcoDesign can open up new marketing opportunities by way of novel types of service." Designing a product as a service is a whole new way of looking at customer needs.
- "EcoDesign is an investment in the future. Public environmental awareness along with governmental environmental policy is growing." This will lead to more laws and producer responsibly. Implementing EcoDesign now means being ahead of the trend and avoiding liability in the future.
- "EcoDesign increases employees' motivation." Doing the right thing feels good.
- "EcoDesign saves our environment." It will conserve precious natural resources and reduce/eliminate industrial waste streams. (Tischner17)

How to do it? EcoDesign is a new and rapidly developing field. It is impossible to instantly make our entire society comply with the principles of sustainability. That is why we call it sustainable development. We currently live in a society based on the progress of the industrial revolution. The industrial revolution sprang up around the belief that there were limitless resources to feed from, and limitless places to put the waste of industry. Simply said, we are living in a society not designed for sustainability. As a result, to get to a place that could be considered living sustainably, we need to redesign everything. We start with various levels of product improvement, and product redesign. But then we will move to rethinking entire industries, materials and processes, and finally entire systems. Systems that rethink what it is to meet the needs of customers. This idea is captured visually by the following graphic:



Level 1: Product improvement: this is a progressive and incremental improvement of the product, a re-styling of the product; for example, it can consist of decreasing the use of materials or replacing one type of fastener with another.
Level 2: Product redesign: a new product is redesigned on the basis of an existing product.
Level 3: new product concept definition: this occurs when technology develops to make new products possible.
Level 4: new product system definition: this occurs when innovation in the productive system is necessary.

Figure 9: Ecoefficiency Improvement Levels, from ECOLIFE, EcoDesign Guide. <http://www.ihrt.tuwien.ac.at/sat/base/Ecolife/ECOIndex.html> 10.

Why is why it so important for designers to embrace EcoDesign? "In the narrow sense, the design stage typically determines most of the lifetime environmental and social impacts of products and services. In many ways this makes it the most important business function for long-term sustainability" (Charter 87). 70-90% of the costs and environmental impacts are locked in by the time research and development start (ECOLIFE EcoDesign Guide). This is because major parts of the design of the product and overall system are already assumed. This is where design up front and early can have an amazing impact, and is why all product designers should be trained in EcoDesign methodologies.

Continuous improvement is necessary to the process of EcoDesign. Results of design efforts should be tracked and learned from. EMS systems will help this effort. Improvement is based on experience. Ideally the information learned should be fed into an easy to use database for designers. Such as what materials are fully recyclable and are appropriate for use.

Concurrent engineering is another process that EcoDesign depends upon. Designing the best product throughout its entire lifecycle means talking to the experts at each stage of the lifecycle. This concept is known as concurrent engineering and is a trend that will continue to grow in importance. Industrial designers, product designers, as well as engineers will all have to be centrally involved in the life cycle of a product. Perhaps this concept should take on a new name, 'concurrent design'.

Once a system of EcoDesign is in place, the only thing left is to follow it.

Below are seven simple steps that have been laid out in How to do EcoDesign?:

Step One: Define scope and task. What is the task and how radical can we be?

Step Two: Analysis of a reference product or of the Problem. What are greatest ecological weaknesses/improvement potentials?

LCA or other evaluation tools. Streamline LCA, checklists, spider diagrams. Then define users needs.

Step Three: Idea generation and selecting ideas.

Brainstorm, develope checklist to meet, plot spider diagrams.

Step Four: Working out realistic solutions.

Work in durability, product as a service, modular design, energy material efficiency. Design for recycling.

Step Five: Final assessment of the drafts.

This step comes between the planning phase and the actual production phase. Apply assessment of all ideas and use tools to select best one.

Step Six: Realization, market introduction

Working out the logistics of the physical design, the marketing plan, price structure, take-back system.

Step Seven: Keeping products/services under review after their marketing introduction. This is a constant learning process in order to continually improve EcoDesign. Be sure to take data, feedback, criticism, on various functions of the product and its life phases.

DESIGN FOR ENVIRONMENT

One section of EcoDesign sets out to give engineers and designers detailed guidelines to help make products more environmentally friendly. In the engineering community there are plenty of guidelines concerning various aspects of design. For example, design for assembly, design for efficiency, or design for injection molding. Design for Environment (DfE) is a set of guidelines concerned with lessening environmental impact of products.

There are two foci of DfE. One focus is centered on expanding the lifecycle view, looking beyond just getting the product into the hands of the user. Product design must now take into account end-of-life systems, which means designing for disassembly and recycling. This changes everything from materials selection, assembly techniques, production techniques, use of the product, and a host of other aspects. The other focus of DfE is to lessen environmental impacts by focusing on dematerialization, and reduction of energy use. DfE is fundamentally changing how products are now designed and how they will be designed in the future.

DfE can be applied to each stage of the product's life cycle. These stages listed in order are product concept development, physical design, production, use, and finally end-of-life. Applied at each of these stages, DfE principles can significantly reduce or eliminate environmental impact.

Concept Development

Concept Development is the first stage where DfE principles should be applied. This should happen before any product is produced or any assumptions about use are made. At this stage, the possibilities are endless. Here lies the biggest opportunity for reduction of environmental footprint. How will the product be used? Who will use it? Is the product filling a real need? Should the product even be made? The following principles target conceptualizing product use.

Dematerialization is the first principle of DfE in the concept development phase. Combine functionality of many products into one. Meet more needs with just one product. Consumer electronics are rapidly moving in this direction. No longer will consumers need separate devices to make phone calls, organized day books, listen to music, play video games, etc.

Product as a service is a great concept that changes the entire game plan of product development. The goal of any product design is to meet the needs of the user. What if these same needs could be met instead by providing a service? This would allow the needs of the consumer to be met and paid for, without necessarily arriving at a physical product to sell. With this model of business, service is sold, not physical goods. A product is only designed and built to act as a means to deliver a service. The service provider may then retain ownership of the physical product, and 'lease' it to the customer.

Because the producers own the product, an amazing shift occurs in design goals. First, because producers have to pay for production, volume, and mass, it will be in their best interest to dematerialize the product. Customers pay more for benefits, not 'stuff'. Second, it will also allow producers to be responsible for the maintenance, recycling, and proper disposal of the product. The producer is likely to handle the product's end-of-life in the most efficient manner. Most importantly, this allows an end-of-life system to develop, where a product can be resold, reused, reclaimed or safely disposed of.

An added benefit to the 'product as a service' system is that the producer will also likely establish a better connection with the customer. When a customer is ready to return a product, it can be traded in for the newest version. This will help build return customers. Also, because of the additional contact of continually providing service, a company will be in better touch with the users needs. These two factors establish more customer loyalty.

Philips Consumer Products developed a line of products known as the "Rent Line" with the idea of product as a service in mind. Some products are meant to be owned and to establish an emotional bond and long-term relationship with their owners, others are only needed for a short term, a certain need, or only while the product is useful. "Today, however, we're very often obliged to buy such temporary products on the same basis and terms as those which we plan to keep with us forever." Product developers need to find a new way to design products that address this variable need for possession. This is what "Rent Line" attempted to achieve (Marzano).

Increase shared use is a third idea that can assist DfE during the concept development stage. It is important to get as much functionality out of a product as possible. This can include designing a product to be used by many people at once, for example, buses compared to cars. Or a product may be designed to serve a number of users consecutively. Often when products are no longer used, they end up in a drawer or box, if they don't go straight to the landfill. A product such as this should be re-used by someone else. If the product is designed as a service, it could easily be collected by the producer and go to another user.

Physical Design

The physical design is the next life cycle phase of product development after concept development. This includes a product's form, aesthetics, construction, and usefulness. In this stage there are many important concepts and guidelines to follow. Physical assembly, materials, and finishes must be handled appropriately to make a design environmentally friendly. A design must also work with the end-of-life system. Cost is a factor at this stage, as well. Products must be designed to be recoverable and reusable in a manner that is profitable. This is seen as a difficult hurdle to EcoDesign. But intelligent design can combine all these factors and allow for innovation.

Many contemporary materials and methods of construction do not co-exist well with the environment. Additionally many materials make products impossible to recycle. These materials and processes should be avoided, even though this may limit many options. The smaller number of environmentally friendly materials and processes can be very restrictive to designers. Huge opportunities exist to redesign materials and assembly systems, but for now, current options must be analyzed and carefully chosen.

Keeping the design simple is very important. The design must be easily disassembled and recycled. Any unnecessary parts will add complexity to disassembly. All parts of a design should be analyzed and combined to limit the total part count. Finishing and decoration can increase energy use and effect recyclability. Any added features should be carefully weighed in a cost/benefit analysis.

Weight reduction decreases the amount of materials used, the cost, and the impacts of transportation. Every little bit helps, as mass production will multiply the effects of a design.

Design products for long life, durability, and reliability. It is important to increase the service given by any product. Design the product to have a long life, and be easily serviceable. Every part of a product should provide as much usefulness as possible.

Design products for repair. Many products are thrown away when they stop working. Typically, when a product stops working, it is the fault of just one malfunctioning component. Making a product easy to diagnose and repair will ensure that its useful life is increased. A product can be designed to make parts easily assessable and replaceable.

Modular component design is a key to design for disassembly, recycling, and reparability. Components should be made and assembled as easily removable modules. One benefit of modular design is that internal components can be designed to be upgradeable. This way, the same product can be given new life and usefulness. This could also be applied to the aesthetics of a product.

The industrial design of a product should attempt to be long lived, called **'timeless design'**. Avoiding trendy styling and designing the product to age gracefully improves a products long-lasting appeal. Finishing should improve with age, not degrade. A bond should be built with a customer, to care for a product and to use it for a long time.

Materials

Materials selection is key to the product's environmental impact, especially during the end-of-life stage. Selecting the appropriate material may be one of the most important aspects to EcoDesign. Drawing on Bill McDonough's methodologies, it is important to note that mass, and material on earth is of a finite amount. It is very important that we utilize the resources available to us in a responsible manner. When we 'throw something away' there really is no 'away'. To throw something away means to make its material inaccessible or unusable. Also poor design can combine materials in ways that make them inseparable. The cradle-to-cradle approach is, at its center, an approach to preserve material resources in a way to last indefinitely.

Hazardous materials should be eliminated or avoided as much as possible. When hazardous materials must be used, as in the case of batteries, they should be designed to be reclaimed and recycled.

Limit variety of materials used in a design. The number of different types of materials should be reduced to aid disassembly and recyclability. Proper recycling of all materials requires that they be easily and fully separated. Even a tiny amount of dissimilar material mixed in can contaminate an entire batch of material.

Use recycled/recyclable materials. Materials must be selected for durability and recyclability. Materials should be able to be fully recycled to 100% of their initial quality to avoid wasteful 'downcycling'. The product design, finishing, and end-of-life system must work together to allow materials to be fully sorted and recovered. Adhering to this principle does eliminate a number of options for industrial design; however with the recovery rates that the WEEE laws require, a new market is quickly emerging for materials that offer traditional physical and aesthetic options with 100% recyclability.

Production

Production ranges from component and subassembly production to product assembly and finishing. Production accounts for the largest waste associated with products. ISO 14000, and its associated LCA methods help to locate this type of waste. There is a good deal of work being done in the manufacturing sector to allow for cleaner production. It is up to the design community to seek it out and support it.

Distribution

The next stage of the lifecycle is product distribution. This includes moving the product through the supply chain. This can include moving components from suppliers to the final assembly, and final assembly to the end user. This applies to both transportation and packaging.

Transportation can use a significant amount of energy. Distribution logistics should be worked out to make this system as efficient as possible. Localized production should be implemented where appropriate. End-of-life systems should be carefully planned, as products will likely be collected and shipped back to the producer.

Packaging should be efficient, recyclable and re-useable. Shipping costs apply to both volume and weight. Both should be reduced as much as possible. Packaging should also be designed to be kept and re-used to return a product to the producer at the end of its life. This same principle can be implemented within the production system, by reusing component packaging from suppliers.

Use

Energy use is often the biggest environmental impact of electronic products. Products should be designed to have sleep or standby modes to ensure they are always using as little power as possible. Cleaner energy should be used whenever possible, such as implementing solar or kinetic energy power into a product.

Consumables should be both minimized and clean. Consumables refer to subsets of materials that a product consumes during its use, such as paper and ink in a copier or filters in a coffee maker.

End-of-life

With extended producer responsibility quickly becoming reality, end-of-life systems are rapidly emerging. The aim is to get as much use out of a product and its components through re-use and to ensure proper disposal and recycling. There are various degrees of re-use that apply to the entire product, components, or just re-using the materials it contains. Implemented solutions must also be financially feasible. Methodologies exist to help companies determine the most economically attractive plan for end-of-life, and ensure that products are re-used to the highest value, be it re-use or recycling.

End-of-life systems are the realization of cradle-to-cradle methodologies. Industrial ecosystems need to be established linking producers, suppliers, distributors, customers, and recyclers. This must all be achieved in a way that both recovers the most embodied energy of the product and its components in a way that is financially feasible. The graphic below from MBDC.com shows the flow paths of such a system.

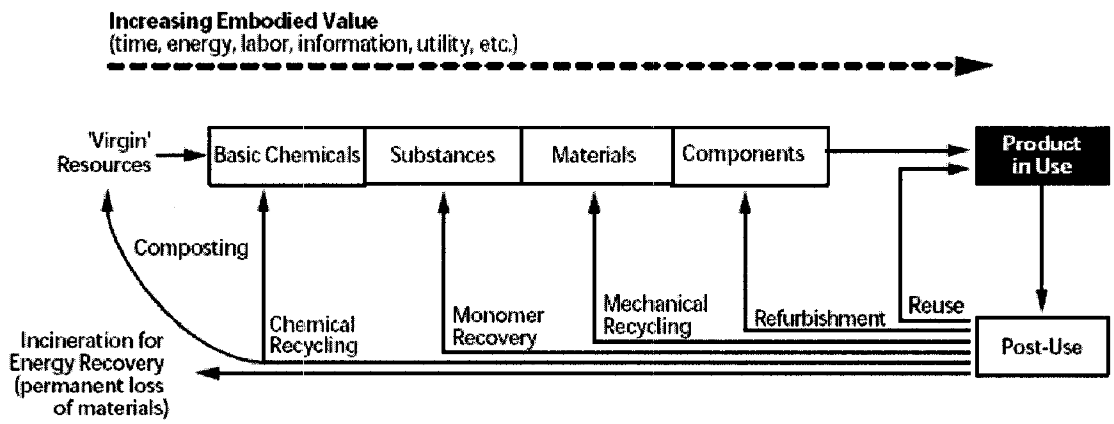


Figure 10: Embodied Value of Materials at End-of-Life Stage, from McDonough Brangart Design Chemistry, Cradle-to-Cradle Design Guidelines. <www.mbdc.com/challenge/ Cradle-To-Cradle_Design_Guidelines.pdf> 5.

Design for disassembly. When a designer designs a product for disassembly, they must meet the following needs. First, components and materials must be easy to separate. Second, it should be cost effective to do so. Analysis must be done to determine the best course of action appropriate for specific parts of the design. In what fashion should the components be reused in order to obtain their highest value?

There are essentially two types of disassembly. The first is shredding and the second is full disassembly. These must be understood in order to know how to design for them.

Shedding is an automated process for disassembly that aims to recover raw materials. It is an extremely cost effective manner to reclaim products that have little value for re-use. However, products must be designed with this end process in mind for it to work effectively. First, hazardous materials, such as

CFCs or PCBs are removed for safe disposal. Next, the remnants are put through a shredder. This breaks the product down into small parts. These crushed parts are put through a series of stations designed to separate materials in order to recover them. Magnets capture steel. Baths of varying densities are used to float particular materials. Because of their high value, most metals are reclaimed. Systems sort plastics into type by using various methods, such as infrared imaging systems. The remaining materials – other plastics, papers, rubber and glass, are referred to as fluff and sent to landfills. The following graphic is a good illustration of such a system.

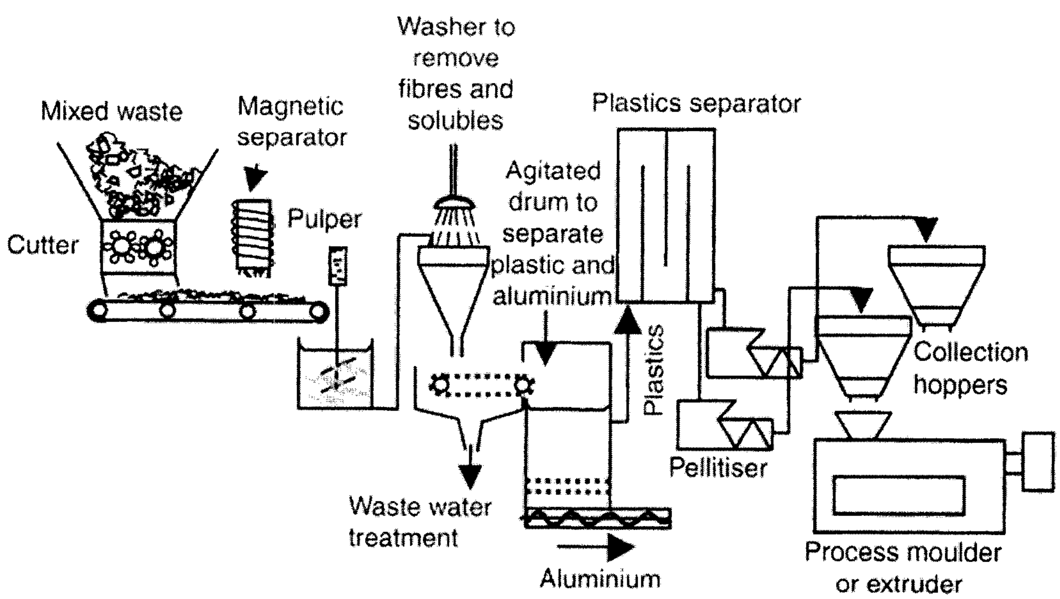


Figure 11: Process diagram for a plastic preparation and compounding unit, from Guneri Akovali, Frontiers in the Science and Technology of Polymer Recycling. (Boston: Kluwer Academic, 1998) 58.

It should be noted that this shredding should only be done if the value of the raw materials exceeds the value of the individual components. When designing with shredding in mind, a designer should avoid permanently combining dissimilar materials. Examples of processes to avoid include the use of screws, which may not separate from bosses during shredding, adhesives or labels, and overmolding of dissimilar materials.

Full disassembly, as opposed to shredding, is a non-destructive way to disassemble a product into its components. The benefit of this system is that parts and components can be reused or remanufactured while they still have a good deal of embodied value in them. For example, most microchips and motors are worth more as full assemblies than as a collection of raw materials. Full disassembly is often a manual process that can be both expensive and time consuming. Designs must be conceived that allow for simple disassembly and easy component recovery. The value of parts recovered must be weighed against the cost to recover them. A cost analysis must be done at every step along the way.

New methodologies are being developed to allow the process of full disassembly to be more cost effective. Many good design for assembly techniques currently in practice also apply to full disassembly.

Stanford graduate students Kosuke Ishii and Burton Lee have formalized a process they call the 'reverse fish bone assembly design' or 'clumping'. In this process, the first step in designing a product is to identify and simplify the components or modules of a product. Next, an end-of-life plan is established for each module based on available options and monetary value. Last, the assembly/disassembly process is designed to arrange modules so they can be removed in appropriate order, with the most valuable modules being removed first. Parts are grouped into major subassemblies, linking similar materials. Arranging components in this way typically improves assembly, cost and robustness (Goldberg 69-82).

Another key to making full disassembly practical is tracking. Tracking serves three functions: identifying location, wear, and when is the optimal time for the product to be returned. The maximum value of a component lies in the ability to get the maximum life from it, yet not to overwork it and have it fail. So, if a component is to be recovered, how can its reliability be assessed? Systems monitoring use and wear can be integrated into reusable modules. This way, during product recovery/recycling, the recycler would know if a component was still good or not. For example, currently 'used' motors get thrown away because of reliability risk. However, if the motor had an integrated electronic data log (EDL) it could read that it has only run for 50 hours, but is certified to run 1000 hours. Another name for this device is micro electro-mechanical systems (MEMS). Having a built in monitoring system not only tracks usage but can also send data back to producers letting them know when it is time for service or disassembly (Goldberg 69-82).

The best method of disassembly will likely be a combination of the two systems, both full disassembly and shredding. As systems progress, automated disassembly will bring the best aspects of both systems, maximizing retuned value while minimizing disassembly cost.

Here are some options and how to tell if they are feasible or not (Hundal 217):

1. Dismantle further? At some stage of the disassembly process, the cost of the disassembly may exceed the value of parts that will be recovered.
2. Send to shedder? If a subassembly of compatible materials is reached, then it might make more sense to recycle them together rather then taking them apart.
3. Sell? Subassemblies are often worth more then the sum of the parts, for example a motor.
4. Remanufacture? Can the cost and environmental effects of remanufacture be less than the cost to covert it back to raw material and make a new product from scratch?
5. Hazardous material in the subassembly? The hazardous materials must be removed from other parts prior to recycling. Also consider the cost of sending the leftover to a hazardous landfill.

RESEARCH CONCLUSIONS

"Complete product recycling is still in its infancy; however, it is becoming more common as a result of product take-back legislation and companies developing product take-back policies. To make disassembly efficient, new recycling processes and designs that are easier to recycle are now being developed"(Lewis 176). These systems will have to be heavily integrated into product design and production. Professional recyclers exist today. However, the trend will lead to them become a more important supplier/customer of major product developers. Just as assemblers and suppliers today give specifications that shape product design parameters, professional recyclers will begin to do so. It is not inconceivable that end-of-life recycling constraints will dictate the selection of entire materials and assembly techniques in order to obtain compatibility of the system. At first, options will be limited, but as the technology develops and the number of customers grows, the number of options for assembly, material selection, and decoration will grow as well. This will be the beginning of the new ‘industrial ecosystem’.

PART III: PROPOSED SOLUTION

DEFINING GOALS

The main goal of this thesis has been to investigate sustainable principles acting as a driving force for innovation and to see how this view would steer the design of personal handheld consumer electronics. Can a sustainably produced product be competitive and innovative? What new insights will life-cycle thinking have on the end results?

It has also been a goal of this thesis to act as a teaching tool. Can the device I design teach and promote ideas of sustainability to the industry and to customers? Because of this goal, this project attempts to remain grounded in what is achievable and feasible in the consumer electronics industry in the near future. As the research suggests, there is a major need for the industry to find implementable sustainable design ideas that allow industry to meet the bottom line. It is important that a project such as this be approached with regard to feasibility to allow for the best chance of promotion of the ideas and adoption of these new principles.

DEFINING PARAMETERS

The previous section covered research regarding current issues, practices and tools of sustainable design in the electronics industry. These must all be well understood in order to arrive at a feasible solution. The attempt was first to find needs for the industry and then the tools available to make a sustainable solution possible. Based on these needs and tools, parameters were formed to govern the specific product design.

Need is an important catalyst of all change. Without a need to change, there is little motivation to do so. This is why regulation is such an important factor for sustainable design. It serves to link the needs of people and our environment back to the producers. People need a safe healthy environment in which to live. The producers are responsible for making the products that ultimately end up being harmful to our environment and to our health. However, there is no inherent need for the industry to change its ways, because there is no obvious link. Intelligent regulation connects these needs to the producer. This extended producer responsibility would not happen without the financial need to make it happen. The costs to governments to clean the environment and care for its people are now being transferred to those responsible for making waste. New laws and heavy penalties give industry the financial need to find new ways of doing business. In the electronics industry, as a result of WEEE and ROHS, it is now in the producers' best interest to produce less waste and reduce the quantity of hazardous materials used.

Tools such as ISO 14000, and Eco Design practices allow the producers to design to meet these new needs. ISO 14000 and LCA tools allow the industry to focus on what key issues to address, but also do so in a manner that serves to help reduce cost. Furthermore EcoDesign and Design for Environment principles also serve as a tool to allow for innovation and arriving at feasible solutions. In addition, companies will use this situation for improving public image by promoting their honest corporate responsibility. This can be used as a promotional tool to boost profits.

EXISTING PRODUCT ANALYSIS

In order to design a future handheld communications device, the current industry and its products must be analyzed. The Eco-LIDS (Eco Lifecycle Integrated Design Strategy) wheel EcoDesign tool was used to perform this analysis. As mentioned in the EcoDesign Tools section, the Eco-LIDS wheel does an excellent job of evaluating a product in the concept phase and helps to set the focus of sustainable design.

The LIDS wheel assumes a general knowledge of the industry and issues surrounding lifecycle design. The wheel consists of an axis for each phase of the lifecycle. Each phase is analyzed and scored on a scale of 1 to 5, 1 being a poor score, 5 being an excellent score. Scoring is an intuitive practice based on research and general knowledge of the product. These scores are then connected around the web. A small area indicates a poor product, a bigger area a more sustainable product. Any low scoring sections should be marked for heavy investigation and ideation. Below are the results for a generic cellular phone. Scoring is based on the previous research and general knowledge gained from my personal experience working in the industry.

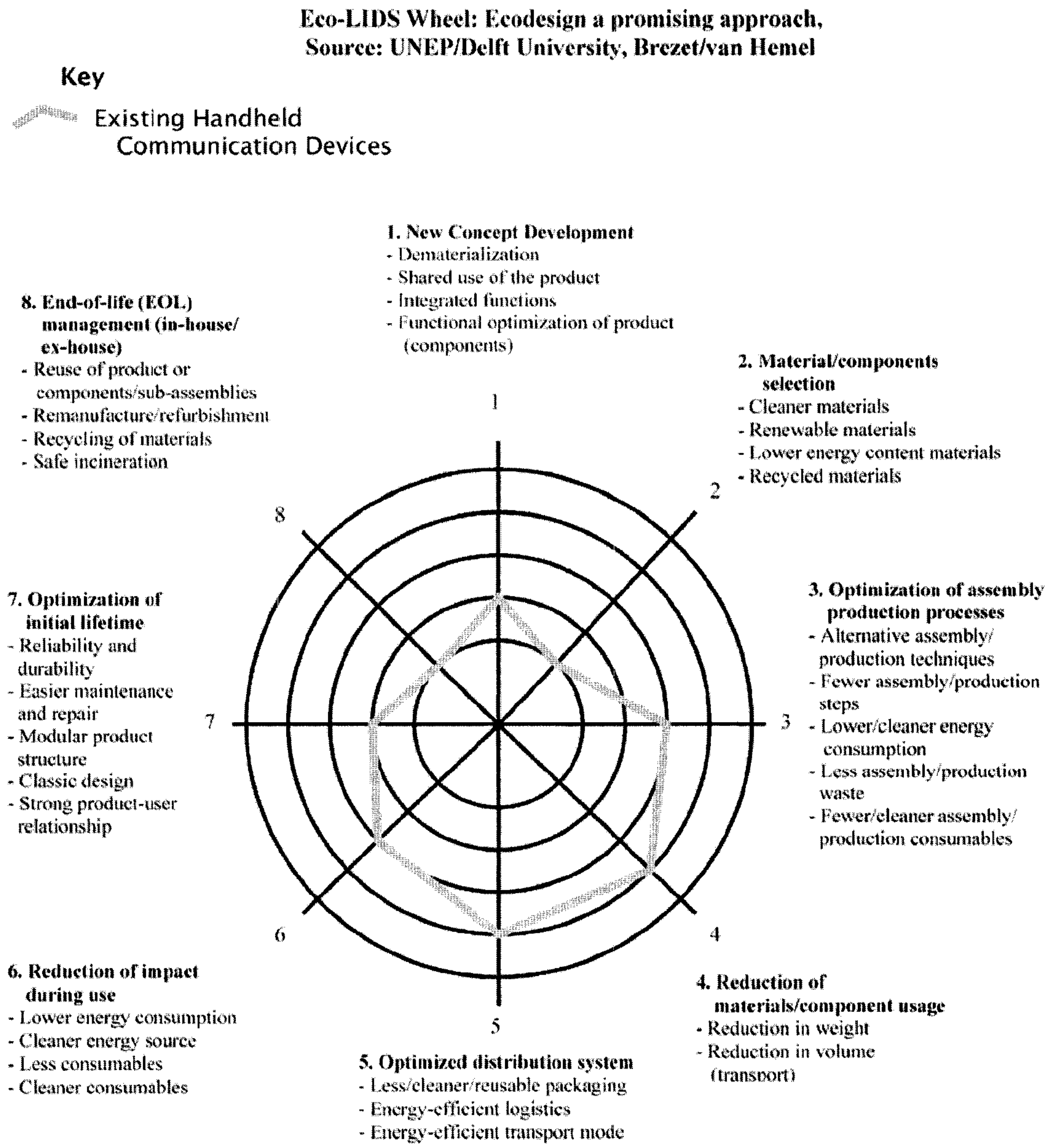


Figure 12: EcoLIDS Wheel with Cell Phone Analysis, adapted from Ursula Tischner, ed., How to do EcoDesign?: a Guide for Environmentally and Economically Sound Design. (Frankfurt am Main: Verlag form, 2000) 97.

Scoring is based on the following issues for each phase (1-8) of the product lifecycle. Referring to the full analysis included in the Appendix, a '+' indicates a positive attribute, a '-' indicates a negative attribute. A score of 1 would indicate that there is no environmental concern for that part of the lifecycle in the industry and is a major source of environmental harm. A score of 5 would indicate that particular phase of the lifecycle is of great concern to the industry and results in little to no environmental harm. Please see the Appendix for the full analysis including the criteria, specific issues, and a final score for each phase.

Overall, the LIDS analysis points out two major flaws with current cellular phone design. The first is 'Material/component selection'. The other is 'End-of-life Management'. These are both major keys to arriving at a sustainable design, and both are currently completely ignored.

Materials/Component Selection

A good score in the 'Materials/Component Selection' category would require using materials that are non-hazardous, and fully recyclable. A poor score would indicate the opposite. Unfortunately, in the case of current cellular phone design, the latter is true. Selection for clean recyclable materials is simply not a criterion in design. The selection of materials is made solely for function and aesthetics. As a result, many composite materials are used to achieve design goals. This permanent mixing of materials renders all materials useless and non-recyclable.

On the function side, a good design is durable, reliable, and mechanically sound. Many different materials are used. A key issue inside cell phones is to make electrically grounded shield boxes around the board components. This is necessary to insure that none of the components on the board interferes with another or any other electrical equipment. A shield box is made by encasing sections of components with a conductive metallic ground plane. Few materials are good conductors, so to get around this issue many materials are plated. Plating a thin layer of conductive material can make a plastic, or any material suitable for shielding, but unfortunately results in a part that is no longer recyclable. Other issues include technologies such as chips or PCBs (printed circuit boards) that are a necessary combination of materials, many hazardous.

On the design side, there are a number of practices that render materials unfit for recycling. Painting is the most common. Paint in even a small quantity can ruin an entire batch of recycled plastics. Plating for a metallic look is another concern. Other practices that make recycling impossible include: overmolding (combining two types of thermoplastics), IMD (in-mold decorating), IMF (in-mold forming), use of adhesives, labels, and non-removable mechanical fasteners. These are all factors that research on DfE (design for environment) principles helped to point out.

End-Of-Life Management

A good score in the 'End-of-Life Management' section would mean that the end-of-life was considered and designed for. Products are designed to fit into a reclamation system to properly dispose of waste, and ensure proper recycling of reclaimed materials. A poor score would indicate that this has not been considered and reusable materials are not reclaimed, and worst of all, hazardous materials are potentially improperly disposed of. Again, unfortunately, the latter is true. In the current system, cell phones are bought by the consumer, and are from then on, the consumer's sole responsibility. Many consumers are faced with the question of what to do with an old phone. Often these devices get replaced every few years, as technology continually improves. There really is no system in place to accept and safely dispose of all these devices. Responsible consumers will donate their old phones for reuse. But this only postpones the inevitable: throwing them in a landfill. This is a very serious health threat and a rapidly rising issue. This is the main motivator for regulations such as WEEE, and ROHS.

One highlight of the current system is how batteries are dealt with. Batteries are potentially the most harmful part of any electronic device. Nearly all the materials used for all types of batteries are extremely toxic. But because of this fact, law requires that a system be in place to reclaim old batteries and properly dispose of them. This system does indeed exist, and in the case of automotive lead acid batteries, is one of the few fully functioning cradle-to-cradle systems. However, the only requirement for industry is that they include a label, reminding the consumer to properly dispose of the battery. There is really no system in place that insures batteries stay out of the landfill.

All responsibility is placed on the end user; as a result batteries are improperly discarded all the time.

Optimization of Initial Lifetime

A good score in this section would indicate that the product is reliable, durable and capable of providing a long service life. Also, if the product breaks down, it can be easily serviceable, and designed to develop a strong bond with the user, insuring that it be used as long as possible. An antique would score very high in this category. Cars would also score fairly high, as it is possible to get many years of service from them. Technically, cell phones are not too different from cars. They are designed to be competitive in the market and thus designed to be durable and reliable. Many companies will service a defective product and get it back to the user, thus being able to offer long life service. If you were able to locate a early 1990s 'bag phone' there is a very good chance that you could still be able to use it to make a call. However, because the industry is always on the cutting edge of technology, the products tend to rapidly become outdated and obsolete. In addition, the industry is set up to give consumers incentive to replace old equipment, thus effectively shortening the initial life.

Summary of Eco-LIDS Wheel Analysis

Based on this analysis, a future handheld communication device should avoid the non-sustainable pitfalls of the current system. Mainly, the product should be designed to optimize performance across the entire lifecycle. Products should not be designed merely to meet the short-term goals of serving user needs. The scope of design should be broadened to ensure the needs of environmental health are also covered. The major flaws of the current system reside in not having an end-of-life plan in place. This also makes it apparent that a product cannot be designed alone. The entire system the product functions within must also be designed to ensure materials are taken back, and properly disposed. This is effectively a cradle-to-cradle system.

OVERALL DESIGN GOALS

By combining what was learned in the research phase, with what was learned in the product analysis phase, a thorough list of goals can be made. It combines the overall needs of systems thinking improvement that the product analysis give, with the ability to arrive at feasibility solutions from understanding the tools of LCA, EcoDesign, and DfE. Overall, the goal is to arrive at a sensible cradle-to-cradle system that could be implemented in the near future in the handheld electronics device industry.

As a result of this research, the following goals this thesis project have been established:

- Expand focus to design for entire lifecycle of product
- Reduce/eliminate waste
- Use materials that are fully recyclable to their original quality
- Design a system to ensure proper product take-back and reuse/recycling of these materials
- Attempt to maintain a feasible implementation

HANDHELD COMMUNICATION DEVICE

This thesis originally set out to design a sustainable cellular phone implementable within three years. But what will a cell phone be in three years? Technology is advancing so rapidly, and allowing for so much more technology to fit in the palm of your hand. What trends are emerging to help predict where this industry will go? In attempt to answer these questions, the following items were considered: competitive analysis, user needs, and industry trends.

Technology is advancing so rapidly; it seems almost anything is possible. PDAs are merging with cell phones. Laptops are merging with PDAs. MP3 audio players are merging with cell phones. Cell phones are merging with cameras. Nearly any combination is possible. Looking at this argument through the lens of sustainability, it is clear that combining devices and adding functions is the way to go. Making one device to replace 3-4 others is an obvious benefit to the environment and our resources. No longer will we be using just 'cell phones', but rather a handheld digital communication device.

After an investigation of trends and needs and technology, the following goals were set. Design a small pocketable device that delivers the following functions:

- Wireless Internet or WiFi (wireless fidelity)
- E-mail
- Telecommunications (Voice-Over IP)
- Video communications

- Camera (5 Mega Pixels)
- Audio Player
- Video Player
- Traditional PDA (calendar address book)
- Documents to go (run PP, Excel, word)
- E-book
- Gaming (limited)
- Local GPS mapping 'Spot Local FM' (directions / couples w/ internet for tourism)
- Data storage (IBM nanotech 'millipede') for micro 100 GB storage
- Bluetooth connectivity

FINALIZED SOLUTION

I will now present the results of my project and explain how research and goals guided my design and led to a new innovative product. This will be presented by going through the entire life cycle of the device and highlighting improvements at each phase along the way.

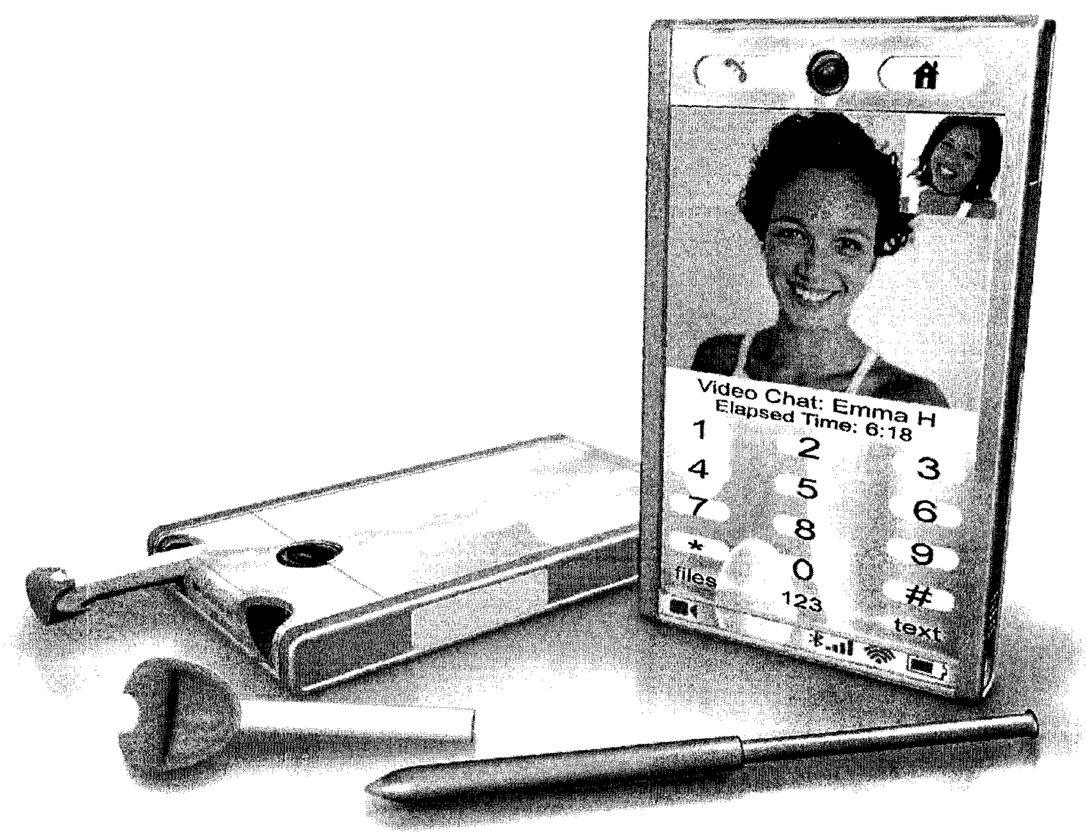


Figure 13: Handheld Communicator Device

Sale: Product finds user

In accordance with cradle-to-cradle principles, the product will be offered as a service. This allows the producer to maintain responsibility for the product and retrieve the components and materials at the end-of-life. Customers know that when the product becomes outdated, they will receive the next model of the device and not have to worry about how to dispose of it. The producer is able to be continually in touch with user needs and maintain good customer relations.

This device will be offered by a WiFi service provider such as 'T-Mobile HotSpot', or 'Boingo.com'. The user simply signs up for the service and pays the monthly fee. The physical device is essentially free.

End-of-life Phase

When the device's service life ends, the producer takes it back. There are a number of benefits to product take-back: component reuse, material recycling, and proper waste disposal. This is an essential step, as there are no material choices that can make a product environmentally benign simply by selling it to the customer and letting it go. This also frees the customer from the burden of deciding what to do with an obsolete device that contains many harmful materials.

It is very important that the end-of-life system be carefully planned to meet a number of requirements, and that the product itself integrates perfectly within that system. Feasibility issues were key in many of the decisions made in designing the system.

The main goal of product recovery is to reclaim materials and components for reuse. It is important first to ensure that materials are selected for recycleabilty and that components are designed for reuse. And second, it must somehow be assured that these materials retain their quality through the use phase and are still able to be recycled. One final issue for end-of-life systems is that they be cost-effective. In addition to intelligent assembly design to quickly reclaim valuable components, automating the process of disassembly is essential to arriving at a feasible solution.

Materials Selection

At this stage of the design, materials must be selected that fit EcoDesign principles. Typical consumer products employ metals or plastics with various finishing processes. Materials must lend themselves to typical considerations of product design, such as mass production and complex part design, as well as aesthetic appeal. The materials selected for this project must also meet the criteria of EcoDesign: safe to produce, use and recycle over and over again in a cradle-to-cradle cycle. These materials are known as cradle-to-cradle materials.

The next paragraphs define the criteria for choosing sustainable materials that integrate flawlessly with the end-of-life management system.

Limit variety of materials

For product design, this criterion means that the materials selected should perform a variety of functions very well. Typically a design will call for the best material to perform each specific function, such as housings, decoration, frames, or attachment scheme. In EcoDesign, materials must be found that can perform as many as these functions at once. Limiting material choices will allow reclamation to be much more feasible, and make recycling easier. The device attempts to use just 3 materials for it basic construction.

Use recycled/recyclable materials

In line with overall goals, I am searching for materials that are not only recyclable, but also recyclable to their full quality. Ideally the material selected should not contribute to downcycling.

Avoid use of toxic materials

Many additives are combined into materials to enhance their performance, such as corrosion resistance or aesthetic enhancements. Decoration and finishing techniques must be carefully evaluated and weighted against their impact on recyclability.

Plastics

Plastic Issues

Plastics are a huge environmental problem. One issue is use, the other is recycling. A lot of plastic is used in industry. In Western Europe, 27.2 million pounds of plastics are consumed each year. 42% of that is for packaging, and 11% is for electronics. In the United States, 30 million tons of plastic are consumed each year. 30% of that is packaging, and 5% is for electronics (Akovali).

Plastics are typically thought of as being highly recyclable. However, this is hardly the case. Very few could meet the above requirements and qualify as cradle-to-cradle materials. Most are actually downcycled.

Akovali defines the following recycling classes:

Primary – reused as same quality plastic, For example sprue regrind.

Secondary – downcycled to alternate use, for example, plastic lumber.

Tertiary – raw material, little value

Quaternary recycling – incinerated for energy

"The most efficient options for recycling both economically and environmentally is 15% mechanical recycling and 85% energy recovery by incineration" (Azapagic 113). Of this 15%, most of that is secondary or tertiary recycling. There are a host of technical and logistical hurdles for full recycling, contamination, sorting, cosmetics to name a few. For the most part, the plastic that comes out of a recycling process, is really not the plastic that went in. A plastic lumber bench seat is really the best that can be hoped for with the current recycling system.

Contaminants

Of engineering plastics that would be used in consumer electronics, there are a host of issues that render recycling impossible or difficult. Most plastics in consumer electronics are used to enhance the cosmetics of a product. As a result, they come in many colors, are painted, plated, metalized, overmolded, in-mold decorated. All these processes end up combining dissimilar materials. These plastics cannot be recycled, because of all the cross-contamination.

In addition to decoration, plastics are also combined with dissimilar materials for other reasons. Labels are placed on them. Metal screws are inserted into them. They may by ultrasonically welded to other types of plastics. It is also possible they came into contact with hazardous materials, such as a leaky battery. These processes are all extremely common and render the plastic non-recyclable.

Sorting

If these non-contaminated plastics were to be reclaimed, other issues arise. Reclaiming materials means sorting them out. After mechanical shredding, the plastics are sorted. Anything going into the shredder must be free of the above contaminates. Sorting is usually done by floating the mixture on various density liquids. This is difficult to do, as many plastics are very close in density. Any contaminants can throw this process off. Once the plastics are sorted, you are left with plastics that are the same density, and hopefully the same type.

Once at this stage, the plastics face a few final hurdles. First, there are a number of additives that are added to plastics to give them certain properties: flame-retardants, plasticizers, glass and or carbon reinforcements, metallic flakes. All these additives are now mixed together.

Secondly, the colors are all mixed up. When combining a batch of random plastic colors together, it ends up just like paint. If you ever mixed a bunch of left over paints, you know the results are not pretty. Usually you get ugly shades of brown and grey.

Third, plastics age. Plastics can age based on environmental conditions such as uv light, temperature or humidity, and surrounding chemicals.

These can cause the basic structure to breakdown. All these issues must be designed for with various additives. These additives tend to breakdown, as well, or change overtime.

What is left is an ugly plastic that likely has various amounts of mechanical degradation. To reuse this, it is commonly mixed in with new plastics, or downgraded to some other use. One clever use is to make it a filler layer sandwiched between new surface plastics. But looking at all these options, they are all clearly downcycled. And, because of all the operations that have to be performed to reclaim plastic- collection, sorting, washing, grinding, repolymerization, transportation- it is more economically feasible to incinerate them to reclaim energy (Akovali).

Plastic Solutions

To give the plastic any chance of being fully recyclable, sorting would have to be much better. Using just one plastic and reprocessing it in-house may even eliminate sorting. The plastic's specific blend, color, additives, age, and environment would all need to be known. This would require that the life cycle be performed in a closed loop. Then after reclaiming the plastic, it can be reprocessed with the correct mixtures of additives and plasticizers to return the plastic to near virgin quality (Akovali).

When used in a closed loop system, plastic selection should be limited. It is conceivable when handled in a closed loop system that it will be possible to reclaim them at near virgin quality. However, colors should be limited to allow for optimal re-use in a variety of applications. Grey or black make sense.

Both ABS and PC are great engineering plastics. “Typical ABS plastic, one of the most common engineering plastics, is very toxic. It is often less then 80% ABS, the rest is flame retardants or plasticizers. ABS is very difficult to properly recycle” (Hundal 439). That rules out ABS. “PC, polycarbonate, is as a very popular engineering plastic. It is generally made from fairly toxic chemicals. However, recent advances have made for a safer PC without harmful chlorine, phosgene, and bisphenol A” (Hundal 439). As a result a plain undecorated grey, or black PC is likely a good candidate for use as a cradle-to-cradle material in this project.

Finding cradle-to-cradle materials seems to an extremely limiting factor for product design. Both engineering and industrial design choices will be limited. With plastics, the likely way to make them fully sustainable is to redesign them. A new set of polymers must be designed with recycling specifically in mind. Also fewer types of polymers to meet the needs of all applications must be designed. Research in this direction is underway and will hopefully be promising (Akovali). With newly developed polymers and an extended closed loop system, various grades and colors will become available as true cradle-to-cradle material options.

Metals

Metals, in general, are relatively harmless to the environment. Most metals were initially pulled from the ground were they lay harmless to the land around them. A few key issues, such as toxic metals and recyclabiliy, should guide selection.

Some metals are toxic and should be avoided. Avoid toxic metals such as chromium, nickel, and tin, as well as harmful coatings such as chromium baths, cadmium, cyanide, and nickel carbonyl for plating.

Steel, aluminum, and magnesium are all commonly used as consumer electronic housings. Generally in housing design, aluminum and magnesium are preferred because they offer lightweight, relative strength, as well as diverse part complexity.

Magnesium

Magnesium has become a popular choice in recent years. It is amazingly stiff, strong and lightweight. New production techniques allow it to be injection molded just like plastic, allowing for limitless design possibilities. However, magnesium is also highly corrosive and thus needs some extensive plating procedures to be useable. It is also known to have a poor surface finish, and requires painting or plating to be used decoratively. Although it is highly recyclable in natural form, the necessary painting and plating complicate this issue.

Aluminum

Aluminum has long been a favorite material in product design. It has a number of great properties that make it an obvious choice. It is light, strong, has great conductivity, and is easily worked. It also has great cosmetics, or appearance. Finally, as it oxidizes it forms a naturally corrosion resistant barrier. This property can be enhanced by anodizing (forced oxidation), which looks great and forms a strong protective barrier.

One main environmental issue is virgin aluminum production. Although it is the third most abundant metal on Earth, it begins as aluminum ore. This aluminum ore must undergo an energy extensive electrolysis procedure to form pure aluminum. This is responsible for its rather high *EcoIndicator99* figure of 780 millipoints per kg, compared to that of PC at 510 millipoints per kg.

However, aluminum is highly recyclable. And used in its recycled form, it is very environmentally friendly. Recycled aluminum consumes 85% less energy and generates 77% less solid waste, 85% less CO_2 and 98% less

SO_x than virgin aluminum (Hundal 339). "Recycling aluminum saves 95 percent of the energy needed to create new aluminum from ore. This translates to approximately 6.5 to 7 kilowatt hours of electricity saved form each pound of metal recycled. Potentially, a total of 53 trillion kilowatt hours could be saved, which is equivalent to 90 million barrels of oil" (Office of Industrial Technology, Energy Efficiency, and Renewal Energy Department, Department of Energy).

EcoIndicator 99 also releases numbers for the recycling of materials. This number is derived from both the impact saved by not processing virgin material and the impact made by the recycling process. Because of the impact avoided by not using virgin aluminum, the indicator is –720 (millipoints per kg). A negative number indicates a helpful process that is actually beneficial to the environment. The included recycling process has a score of 60. Although there is no specific number for PC for comparison, other plastics score –250, with processing at a higher 86. This goes to show that recycling aluminum will pay off to a greater extent with each recycling, compared to plastics. And as a result, aluminum should be incorporated more than plastics in a design where they are comparable.

There are some issues with the current recycling system and what grades of aluminum are available. Currently in the United States, aluminum is recycled all together. All the alloys are mixed and made into one grade of aluminum. This can be used for cans, or casting, but often not the original purpose. Because of the demand for aluminum in the automotive industry, recent advances in recycling technology makes it possible to sort all the various alloys of aluminum. Using a laser identification system, aluminum can be sorted out to various alloys. In this way, the recycled aluminum can now match the quality of virgin aluminum. An even simpler system would be to recycle small batches of a known alloy all together.

There are various production techniques available to form aluminum: for example casting, stamping, and extrusion. Of all these, stamping is the least energy intensive. It is frequently used in product design and allows for a beautiful aesthetic. However, complex parts usually require casting.

Chip Sets

Chip sets seem to be an ideal candidate for reuse. "New electronic products are replacing old ones at an astronomical rate. These outdated ones are often in excellent condition. Chip sets can be harvested from these electronics for re-use. And often at a higher reliability than comparable new ones, because they have survived the burn-in period" (Goldberg 71). Because of the way the technology industry operates, many of these chip sets become obsolete rather rapidly. To insure optimum reuse, the chipsets should be recollected before they become obsolete. Many of these chips can be reused on the next version of a product.

End-of-life systems

Based on the needs of the materials and components to guarantee the highest quality and quantity of useable parts, two factors must be designed into the end-of-life system. First, a type of EOL system must be chosen, individual or collective. Second, the timeline must be set, for service life.

There are two options for selecting a type of end-of-life system: collective responsibility, or individual responsibility. Collective responsibility is a system of a few huge recycling companies that would have the ability to sort every product from every manufacturer, and be able to sort the entire stream into individual components and materials. Although collective responsibility frees the individual manufactures from having to be concerned with product take-back and design for disassembly, all products would have to be designed to meet some minimal requirements of the industry. Secondly, if a product is not designed correctly, it could contaminate the entire batch of materials that it is recycled with.

Individual responsibility is a system where each individual producer collects and recycles their own products. This usually results in a smaller custom built process tailored specifically for the specific products.

There is currently a debate as to which system is better to use, in terms of cost, benefits, feasibility and ease of integration into the current system. It is clear that most of European companies favor individual responsibility, whereas the US seems to favor collective responsibility.

> "Individual responsibility encourages competition in the environmental performance and rewards improvements. Collective responsibility makes environmental improvements pointless and rewards the irresponsible and the lazy."
> --Electrolux (Clean Production Action Home Page)

> "WEEE mandates that individual electronic manufacturers take back their products at the end-of-life as well as design out harmful materials and meet recycling/reuse targets. Manufacturers in Europe not only supported the EPR legislation, but also advocated for mandated individual responsibility, which means corporations have to take back their products independently. Individual responsibility is critical to helping manufacturers redesign products, as the alternative system, whereby companies fund a third party to

collectively take back products, does not reward companies who improve the environmental design of their products. ...Unfortunately, US-based affiliates of the same multi-national companies supporting EPR in Europe, are advocating for consumer funded, government run recycling programs whereby the manufacturer has no role in the end-of-life management of their products. This double standard within multi-national companies runs contrary to the noted economical benefits of global standards that promote consistent policies" (Clean Production Action Home Page).

This device's use of individual responsibility will mean more design freedom, a higher recycling rate and maximum return of material value. Designing for a collective responsibility recycler would likely mean having to follow strict design regulations. This device can be designed with a custom system of collection totally integrated with the latest needs on innovations of the product. Specific materials and components can be selected. And innovative thinking will result in huge benefits and cost savings to the producer.

Self-Disassembling Electronics

Now that the end-of-life system is in place, how can it be optimized to be most economically feasible? DfE provides a host of suggestions on how to make this happen, such as the reverse fishbone design technique, where valuable components are clumped together and easily removed during disassembly. One of the biggest issues, however, is how to avoid huge labor costs in disassembly. This new device must be designed for automated disassembly.

"Since the labor for disassembly represents a large fraction of the cost of recycling electronics, the concept of products that take themselves apart is intriguing…In theory, products designed to actively disassemble themselves would need only minor changes to their internal structures to allow releasable fasteners or actuators to be incorporated into their assemblies" (Goldberg 267-268).

In the proposed solution, this is accomplished through the use of metallic shape-memory alloys (SMAs) in a system named ADSM (Active Disassembly using Smart Materials), developed by Chiodo and Billet, of Brunel University, UK. Below a certain transformation temperature, memory metals behave like standard engineering materials, but above this critical temperature, they undergo a specific shape change. As the temperature changes, a fastener can be triggered to unlock, thus disassembling part of the product. Because this temperature change can be set at various temperatures, putting a product through a range of temperatures can sequence a series of disassembly operations. This will allow products to be easily disassembled and materials to be easily sorted (Goldberg 267-280).

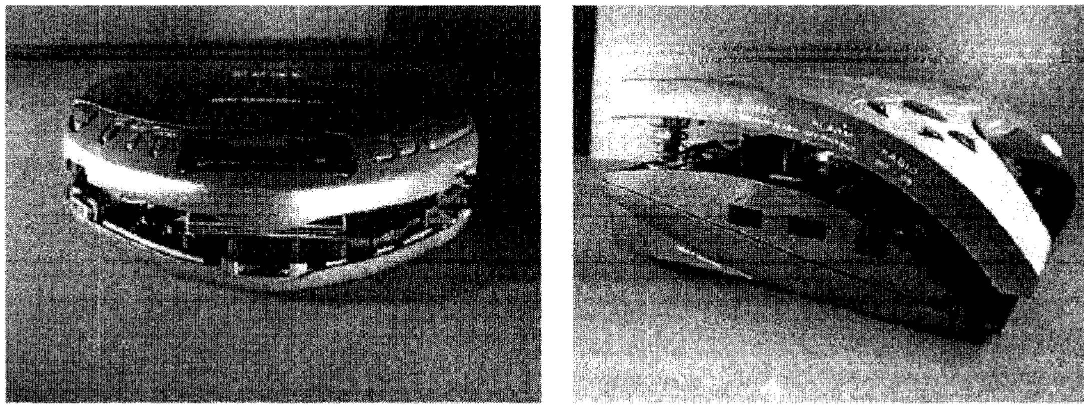


Figure 14: Successful active disassembly experiment – Sony CD player/ Philips radio, from Lee H. Goldberg and Wendy Middleton, Green Electronics, Green Bottom Line: Environmentally Responsible Engineering. (Boston: Newnes, 2000) 277.

In their experiment, Chiodo and Billet, were able to retrofit existing consumer electronic devices with the SMA self-disassembly system. Some of the products included in the study were: Motorola cell phones, Sony CD player, Sony Playstation controller, Philips clock-radio, and a Kodak digital camera. Of the 21 products tested, more than half were successfully made to self disassemble.

VERIFYING IMPROVEMENTS

The results of the new system were analyzed to verify improvements. This analysis was completed on the same LIDS wheel as the initial cellular phone. This is yet another great aspect of the LIDS wheel system, the ability to compare two products quickly in a visual format. The results of this analysis are shown below:

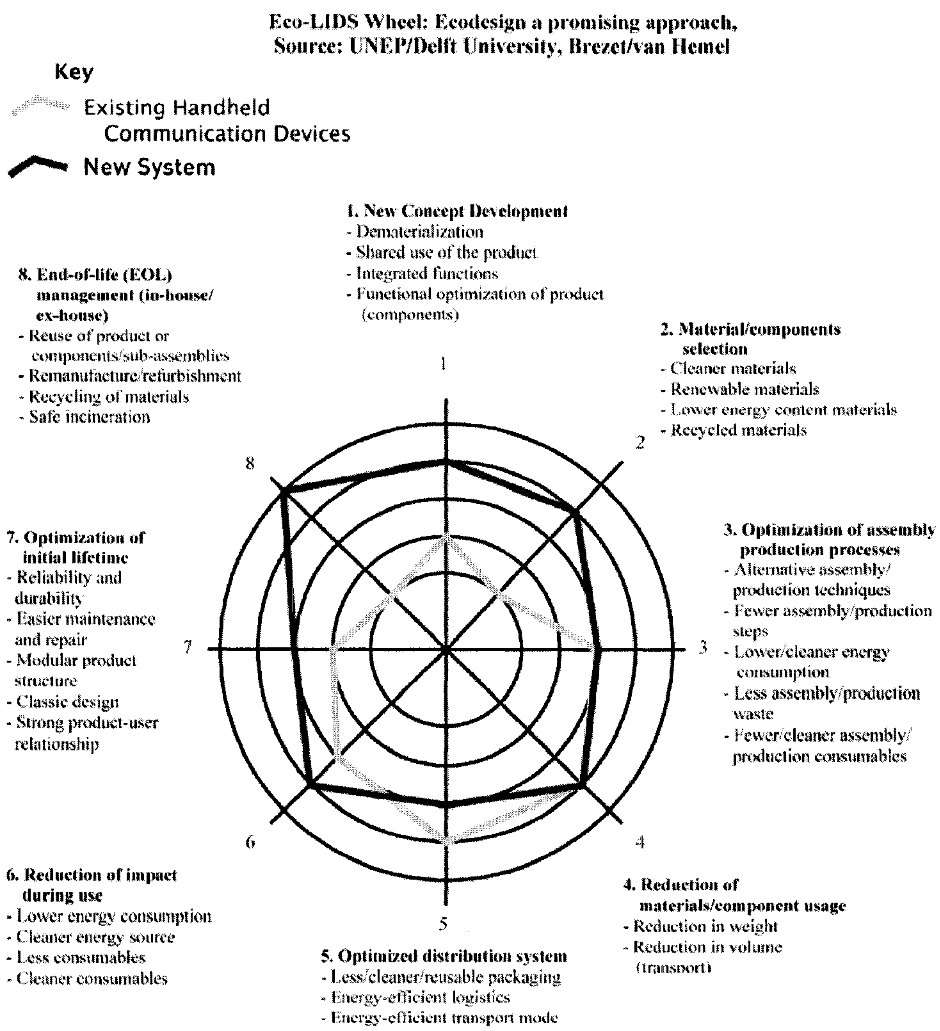


Figure 15: EcoLIDS Wheel With New System and Cell Phone Analysis, adapted from Ursula Tischner, ed., How to do EcoDesign?: a Guide for Environmentally and Economically Sound Design. (Frankfurt am Main: Verlag form, 2000) 97.

Looking at the graph, the new system's profile has a much larger area. This means that it is a much more sustainable device. See the complete analysis in the Appendix. There were two main goals: first, to use only fully recyclable materials, and second, to design a system ensuring materials are reclaimed. These are mainly targets 2 and 8 on the diagram.

For the material/component selection section, a score of 4 out of 5 was given. Approximately 90% by volume of the material is recyclable. Any process that would hamper recycling was avoided. All materials were specifically selected based on this criterion. The score is not perfect, as the new system still contains a number of toxic materials that cannot be avoided.

For the EOL management section, a score of 5 was given. This was really the key to the entire concept and heavily affected every aspect of the design. The best currently available methods of end-of-life were used and fine-tuned to arrive a somewhat feasible system.

It would be nice to see the new system have a perfect 5 in all categories. Unfortunately, many compromises were made to arrive at a feasible reclaimable design. This is the most important aspect of cradle-to-cradle design, making informed compromises throughout the lifecycle in order to arrive at the best design solution. For example, transportation and distribution suffer, because of the additional transport needed to get product back to the manufacturer. Items such as 3 and 4 also suffer. It is difficult to make the most efficient production processes, when choices of materials and construction are so constrained. Overall, the tradeoffs were well worth the gains.

At this stage, there are still many industrial and technological improvements that need to take place in order to fill the LIDS wheel. New cradle-to-cradle materials need to be developed as well as more remanufacturable components and systems. This means that there is a lot of room for improvement, and much more exciting work to be done in this field. We truly are at the beginning of the Next Industrial Revolution.

PART IV: CONCLUSIONS

RESTATE GOALS

The main goal of this thesis has been to investigate sustainable principles acting as a driving force for innovation and to see how this view would steer the design of personal handheld consumer electronics. Can a sustainably produced product be competitive and innovative? What new insights will this view and life-cycle thinking have on the end results?

It is also a goal of this thesis to act as a teaching tool. Can the device I design teach and promote the ideas of sustainability to the industry and to customers? Because of this goal, this project attempts to remain grounded in what is achievable and feasible by the consumer electronics industry in the near future. As my research suggests, there is a major need for the industry to find implementable sustainable design ideas that allow industry to meet the bottom line. It is important that a project such as this be approached with regards to feasibility to allow for the best chance of promotion of the ideas and adoption of these new principles.

PROJECT ACCOMPLISHMENTS

This thesis attempts to demonstrate a solution that is both sustainable and feasible in the near future. Cradle-to-cradle methodologies and lifecycle thinking seemed restrictive at first. Intensive research had to be done to seek out viable and feasible solutions. But this new approach arrived at a number of innovations:

- Arriving at a massive beneficial product-as-a-service solution
- Developing a dematerialized service that offers expanded usable functionality in one convenient product
- Broadening market appeal by offering expanded customizability
- Offering virtual swappable covers that allow for any aesthetic you can dream up in a dematerialized fashion
- Using construction materials that meet all the demanding needs of handheld consumer electronics, yet are 100% recyclable
- Developing a simple assembly technique that is also simple and cost effective to disassemble
- Developing a system of component reuse that prevents valuable and hazardous components from arriving at a landfill
- Isolating all the toxic non-recyclable materials necessary to consumer electronics in one unit that is small and easily reclaimed
- Seeing that the product integrates into a larger tracked take-back system that eases reclamation issues, puts the producer in better contact with the customer, and ensures the producer is able to always offer the latest greatest product
- Allowing the manufacturer to promote honest corporate responsibility

RECOMMENDATIONS

To make it easier for sustainable design to come to fruition in the product design community, a few needs should be addressed. Sustainable design and lifecycle thinking require a much broader view and understanding of what product design is. First, more options are needed for materials and systems to help arrive at sustainable solutions. Second, information availability and interdepartmental cooperation will need to be further developed. An advanced system of information exchange would make this possible.

New technology, materials, components are needed that are designed with recycling in mind. The selection of materials was a particularly constrictive aspect to this project. It was shocking to find how few cradle-to-cradle materials are actually available. So many of the current materials are simply not recyclable today (recyclable meaning returning them to 100% of their virgin quality without downcycling). This will continue to be the biggest short-term restriction to designing sustainable products.

Because handheld electronics are so small, the materials used in them have to perform a variety of functions. They must have the ability to be: lightweight, strong, thin, durable, corrosion resistant, interactive, prevent electrical interference, and aesthetically pleasing. Often, to meet these criteria, many materials are combined together, usually in ways that render the materials non-recyclable. Designing one or a few materials that meet all these criteria and are recyclable will be challenging. But this is exactly what is necessary and what will be in demand. These new cradle-to-cradle materials will allow design to continue to be innovative and boundless rather then restrictive.

We are still in the beginning of a rapid transition in manufacturing technology. All of our technologies are the culmination of putting things together. Many of these things are put together never to come apart. In the future, we will become experts at developing new types of technology to take things apart.

Also new technologies will likely come along and change everything. Nanotechnology, and thermodepolymerization are views of that future.

Another need of this rapidly developing industrial revolution will be for new levels of information exchange. Effective sustainable design is only possible by examining every part of a product's entire lifecycle. Each part of the lifecycle must be optimized in a way which ensures the best overall environmental performance of the product. This demands that the entire product team, from design, through production, distribution, and end-of-life, understand each other and are all informed enough to make intelligent compromises. Compromise is a necessary part of every product design, but even more so in sustainable product design. In the engineering world, this is known as concurrent engineering, but the practice will need to be broadened to be more inclusive, perhaps renamed as concurrent design or concurrent product development.

In particular, more information will be needed for initial concept design teams. Clearly the most beneficial stage of sustainable design, the biggest innovations and improvements come from early concept design. This is why I feel, and research agrees, that industrial design is a key to developing a new sustainable industry. Industrial designers are best at understanding user needs and then bringing solutions to meet these needs. Meeting these user needs is really the core function of any business, and new ways need to be sought out to do this. Designers are very good at the kind of thinking needed to arrive at innovative ideas that will take industry in the new directions it needs to go.

In order to do an effective job, designers need to be able to do what they do best: design. They should not be required to turn into experts on the materials and systems that make sustainable design possible. In the development of this thesis, I had to perform a good deal of research outside the traditional design realm in order to arrive at a sustainable product design. I had to invest a lot of time to achieve a good understanding of many technical issues. Issues such as: the intricacies of materials, the recycling industry, product architecture, and disassembly techniques. Luckily I felt very comfortable researching in this field, as I have a prior degree in engineering and am experienced in product development. However, most industrial designers do not have this luxury.

Industrial designers will need to have access to easily understood reliable information from a variety of sources. Information such as what materials are full cradle-to-cradle materials, what are acceptable decoration options, what role these decisions play in the set up of an end-of-life system. Systems must be implemented to make this information gathering easier for designers. They should have knowledge of EcoDesign basics, but be able to turn to databases or experts for more complex questions.

I believe that this sustainable future is inevitable and not too far down the road. Inevitable, because on one hand, it is a fact that our resources are indeed of a finite amount. On the other hand, pollution of our environment and the heath effects it causes is developing into an advanced science. The new EU laws prove that the cost of protecting our health becoming too expensive to continue the ways of our current industry. Regulations such as these pose a trend that will only continue. But as the industry moves into sustainable development, involuntary or not, they will find it feasible and beneficial. This new way of doing business promises to be very innovative and exciting. Hopefully, this project gives a glimpse of that potential promising future.

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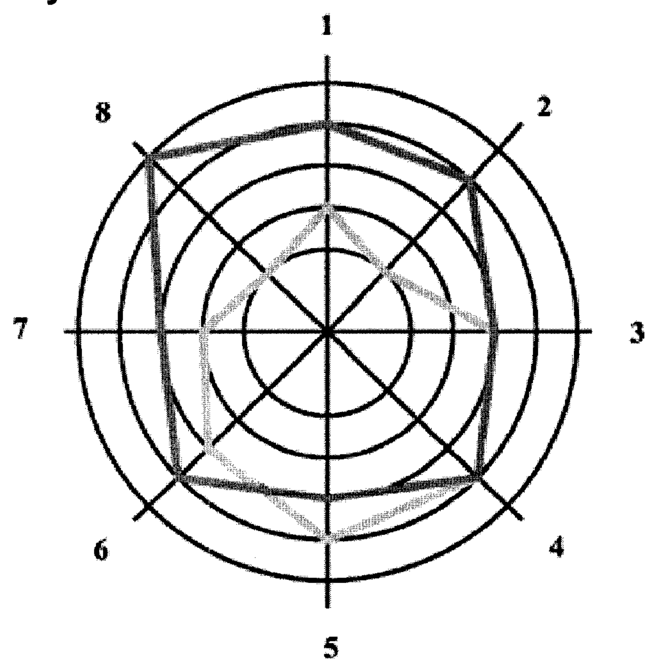
Appendix: Full Eco-LIDS Wheel Analysis

Eco-LIDS Wheel Analysis:

New System vrs. Current Cellular Phones

Source: UNEP/Delft University, Brezet/van Hemel
Analysis: Brett Christie 9-15-03



Key

Existing Handheld Communication Devices

New System

Lifecycle Phase	Cellular Phone		New handheld communicator	
1. New Concept Development - Dematerialization - Shared use of the product - Integrated functions - Functional optimization of product (components)	+ Cell phones are gaining functions replacing other devices - Primarily single use of product	2	+ Added functions replace nearly all common handheld devices + Shared reuse of components and materials	4
2. Material/components selection - Cleaner materials - Renewable materials - Lower energy content materials - Recycled materials	- Many common practices that make for non-recyclable materials - Painting, plating, IMD, stickers, adhesives also make materials impossible to recycle	1	+ Approx 90% recycled materials + Materials specifically selected on this criteria - Still many unavoidable hazardous substances in components	4
3. Optimization of assembly production processes - Alternative assembly/ production techniques - Fewer assembly/production steps - Lower/cleaner energy consumption - Less assembly/production waste - Fewer/cleaner assembly/ production consumables	+ Designed for quick cost effective assembly - Painting/plating and other processes often are not environmentally friendly	3	+ Extensively simplified assembly - More production in reclamation and disassembly	3

LIDS Wheel Analysis (con't)

Lifecycle Phase	Cellular Phone		New System	
4. Reduction of materials/component usage - Reduction in weight - Reduction in volume (transport)	+ Reduction of weight and size is always a big goal for both cost and user appeal	4	+ Compact versitile design - Some mass and volume added due to added functions, reduced cost constraints of material use, and to achieve design for reuse	4
5. Optimized distribution system - Less/cleaner/reusable packaging - Energy-efficient logistics - Energy-efficient transport mode	+ Very efficient cost driven transportation system - Often transported from Asian manufactures - Disposable packaging	4	- Will require additional transportation for remanufacture + Closed loop packaging returns to factory	3
6. Reduction of impact during use - Lower energy consumption - Cleaner energy source - Less consumables - Cleaner consumables	+ Design goal to extend battery life thus designed for low energy use - Plugs into wall to recharge and thus can not guarantee it in running of clean energy.	3	+ Solar powered to insure clean energy source	4
7. Optimization of initial lifetime - Reliability and durability - Easier maintenance and repair - Modular product structure - Classic design - Strong product-user relationship	+ Designed for durability and reliability - Planned obsolesce render product soon useless/unwanted - Trendy design don't age well - Non-Modular	2	+ Designed for durability and reliability + Designed for broad appeal - Use is only for one year.	3
8. End-of-life (EOL) management (in-house/ ex-house) - Reuse of product or components/sub-assemblies - Remanufacture/refurbishment - Recycling of materials - Safe incineration	- Not considered in the design - All up to choice of end user. + Recommended the batteries be recycled and a system is set up to do so	1	+ Entire system designed to achieve this goal	5
Overall Score	22/40		30/40	