THE PROCESS OF DESIGN FOR ENVIRONMENT WITHIN GLOBAL MANUFACTURING COMPANIES

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Submitted to the Department of Civil and Environmental Engineering and the Sloan School of Management in Partial Fulfillment of the Requirements for the Degrees of

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Abstract

Design for the Environment (DfE) is defined as a systematic methodology for reducing the environmental impacts caused by a product by altering its engineering design. In practice, DfE takes many forms depending on the motives and resources of the design team involved. Seldom is a complete "Life Cycle" approach utilized, and the lack of an accepted set of metrics merely adds to the confusion.

Design for Environment (DfE) is commonly referred to as a design *process* in which environmental attributes are treated as design objectives[1]. Because DfE is an immature process, it benefits from a TQM approach of continuous improvement.

> *"According to TQM because every product or service is the outcome of a process, the effective way to improve quality is to improve the process used to build the product[2]."*

Thus, we suggest that focusing on the process of DfE is the best approach to take in formulating DfE strategies. The product development process is a key competitive area for many companies and cannot be disrupted. It is desirable to improve both systems by focusing on the process of DfE within the context of product development. Our research on DfE within industry is based on a literature survey and interviews with the various sectors of the sponsoring companies.

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[1] Office of Technology Assessment; Green Products by Design, Page 7

[2] Shiba, Graham, Walden; A New American TQM, Page 45

The methodology we developed in this thesis begins by conceding that there are still many unknowns, controversies and value judgments inherent in product environmental performance measurement. Rather than attempting to gloss over, or rationalize these difficulties, we include accounting mechanisms for measuring and tracking the uncertainty and incompleteness of the information. Our system utilizes this information for management decision making. The result is a DfE methodology that will improve together with the environmental performance of the products that it is applied to.

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1. Thesis Introduction

1.1 Background

1.1.1 End-of-Pipe Environmental Management

Management of the environment in the 1970's focused on pollution control. The approach was to adopt end-of-pipe solutions focused on single media emissions: land, water or air. The focus on single media resulted in not necessarily a reduction in waste generation but a transfer of waste from one media to another.[3] As a result, the 1980's saw a trend towards pollution prevention and waste minimization over traditional end-of-pipe solutions.

1.1.2 Pollution Prevention

This change in attitude within companies made it possible to get the participation of other functions within the company to address environmental issues that were previously in the domain of the environmental staff. For example, the substantial reductions in US industry environmental emissions since 1986, has been due in large part to the involvement of the manufacturing function, as evidenced by the EPA's annual "SARA"(Superfund Amendment Reauthorization Act) report. Hewlett-Packard reported "SARA" emissions have been reduced by 76% since 1987.[4] Dow Chemical's "Waste Reduction Always Pays" program, has engendered more than 700 projects since 1986,

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[3] For example, in the 1970's the focus of regulatory agencies was the polluted waters and poor air quality. This focus on air and water, through the Clean Air Act and Clean Water Act, resulted in hazardous waste being dumped in landfills. The single media approach to the environment caused companies to focus on the symptoms of the problem, rather than the source of the problem (i.e. factories).

[4] "Hewlett-Packard's Approach to Creating a Life Cycle (Product Stewardship) Program", IEEE Electronics and the Environment, May 1995. Orlando, FL.

saving millions of dollars a year. Westinghouse's "Achievements in Clean Technology" project, formalized in 1989 has had similar results. In one Westinghouse metal finishing factory, the company cut dragout (the contamination accidentally carried as chemical flow from one tank to another) by 75% simply by shaking the tank to remove solids before releasing the chemical to the next tank.[5]

Another example of waste minimization, is the electronic industry's unprecedented progress in eliminating the use and emissions of ozone-depleting substances, mainly cholofluorocarbons (CFC's) and trichloroethane (TCE) in their worldwide manufacturing processes. One of the keys to the success of this program was the sharing of responsibility with the manufacturing organization. Companies relied on manufacturing as the elimination effort required a redesign of many key manufacturing processes.

1.1.3 Beyond Pollution Prevention

However, this focus was still limited to only manufacturing processing and specific chemical pollutants. In the 1990's, drivers such as Germany's proposed take-back legislation and US EPA's Energy Star Program are again changing the way corporations view environmental management. Many companies are trying to adopt a broader, life cycle approach to environmental programs. One approach is to view product design as the focal point for

[5] "What Does it Mean to be Green?", Harvard Business Review, July-August 1991.

addressing environmental issues. During product design, many of the key material and process choices are made that will ultimately effect the environmental impact of a product during its life cycle. The design tradeoffs often are not obvious.[6] In the following chapter we provide an overview of such an approach that is being developed and practiced by an increasing number of companies - *Design for the Environment (DfE).*

1.2 Context

This work was undertaken in the context of the Leaders for Manufacturing (LFM) Program. The LFM Program is a joint effort between the Massachusetts Institute of Technology (MIT) and a number of manufacturing firms and represents a partnership between academia and industry. The purpose of the internship is to apply the understanding of fundamental principles to contemporary business situations.

This particular internship demonstrates the spirit of that partnership as it involved the cooperative effort of two of the sponsoring companies. Their collaboration on this project is a noteworthy attempt to leverage the resources of the LFM program.

1.3 Organization of Thesis

This thesis is organized into five main chapters.

[6] For example, the modern potato chip bag consists of a complex combination of materials which effectively prevents its recycling. On the other hand, the package improves shelf life significantly thus reducing food waste. (Source: Council on Plastics and Packaging in the Environment.)

In chapter two, we provide an overview of DfE based on a literature survey. This overview includes an explanation of DfE and several common DfE practices found within manufacturing companies.

Chapter three discusses the findings of our DfE survey at the two sponsoring companies. Specifically, we present examples of various DfE activities.

Chapter four analyzes and discusses the benefits and areas of concern of the DfE activities discussed in Chapter three. Our review is based on our experience with DfE and the sponsoring companies.

Chapter five presents our proposed DfE methodology for manufacturing firms. The chapter provides a detailed explanation of the methodology together with a practical design example.

Chapter six concludes our thesis by presenting an implementation plan for companies planning to adopt our DfE methodology. In addition we enumerate some of the issues that remain to be addressed.

2. A Survey of Design for Environment Theories and Practices

2.1 What is DfE?

Design for the Environment is a systematic approach that helps to ensure that all relevant environmental concerns and constraints are integrated into a company's product development process. The goal of DfE is to achieve environmentally preferable manufacturing processes and products while maintaining desirable product price/performance characteristics.[7] These can be defined as products that both maximize conservation of resources throughout their life cycle and minimize undesirable environmental impacts.

The scope of DfE encompasses many disciplines, including product safety, occupational health and safety, pollution prevention, resource conservation and waste management. Figure 2-1[8] shows a breakdown of DfE disciplines, many of which are practiced by manufacturing firms today.

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[7] Allenby, B.R. 1991. Design for Environment: A tool whose time has come. SSA Journal September: 5-9.

[8] Microelectronics and Computer Technology Corporation, "Electronics Industry Roadmap", p. 19.

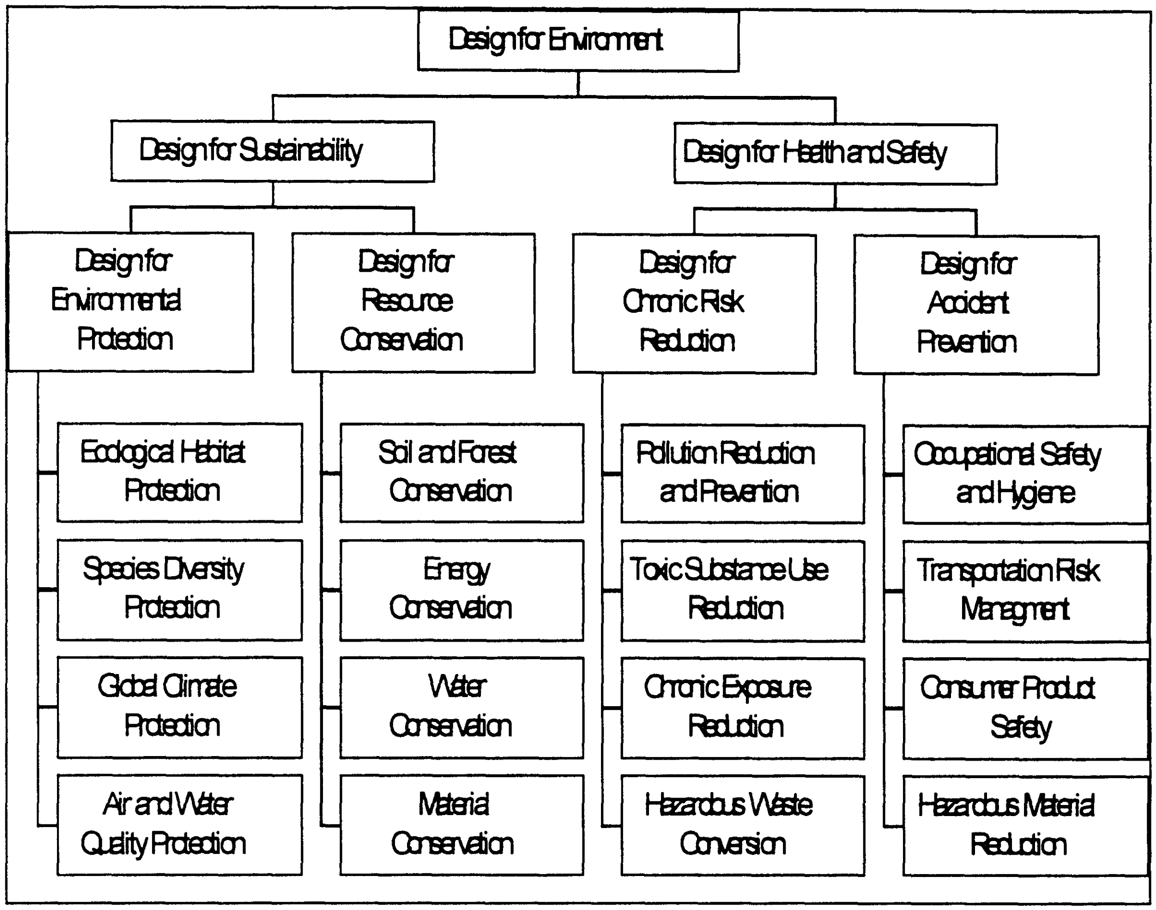

Figure 2.1: Environmental Disciplines

Specific DfE methods have emerged to address the different areas of concern shown in Figure 2-1. For example, reducing the mass of a product can result in both energy and material conservation, which contributes to sustainability, and reduced pollutant emissions, thus contributing to health and safety.[9] The

[9] Ibid.

broad scope of DfE suggests that the effort required for companies to practice DfE is not trivial.

The philosophy behind DfE is similar to that of Design for X (DfX). The concept of DfX was developed to address the lack of integration between product design and other functions resulting in products that were difficult to manufacture, install, service and maintain. This lack of forethought resulted in redesign, production expenses and delayed market entries.[10] Similarly, the lack of integration between product design and environmental engineering has made it difficult to reduce the environmental impact of products, which is necessary to meet increasing environmental regulations and customer requirements.

Just as the emphasis on DfX is on preventing defects early in the product development process rather than finding them further downstream, so to is the emphasis of DfE. Linking DfE to a familiar design process lends credibility to its integration within the product development process and reduces the culture shock of including it as a design consideration.[11]

As DfE can take on a broad context of issues, we use the following definition for DfE:

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[10] Gatenby, David and Foo, George, Design for X (DFX): Key to Competitive, Profitable Products, AT&T Technical Journal, May/June 1990.

[11] Allenby, Brad. Design for Environment. The Greening of Industrial EcoSystems. Washington , D.C. 1994.

> *Design for environment is the systematic process by which firms design products and processes in an environmentally conscious way based on industrial ecology principles across the entire product life-cycle.*[12]

This definition highlights several important points about DfE (Lenox and Ehrenfeld, 1995):

1. Environmental impacts across the entire product life cycle are considered.
2. Impacts are considered during the product development cycle.
3. Decision making is guided by a set of principles based on industrial ecology principles or some set of system-configured, integrative principles.

DfE considers the entire product life cycle. Whereas other approaches include only particular phases of the product life cycle. The product life cycle includes all of the material and energy flow associated with a products primary production to its ultimate disposal, as shown in Figure 2-2[13].

The basis of DfE is similar to the holistic approach of industrial ecology. Industrial ecology is based on the premise that industrial systems are similar to natural ecosystems. Natural ecosystems are waste-free, all by-products are contained and used within a system. Energy and materials flows are conserved. The fundamental basis of industrial ecology is its consideration of the entire life cycle from cradle to grave.

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[12] Lenox, Michael and Ehrenfeld, John: Design for Environment: A New Framework for Strategic Decisions. Total Quality Environmental Management, Summer 1995.

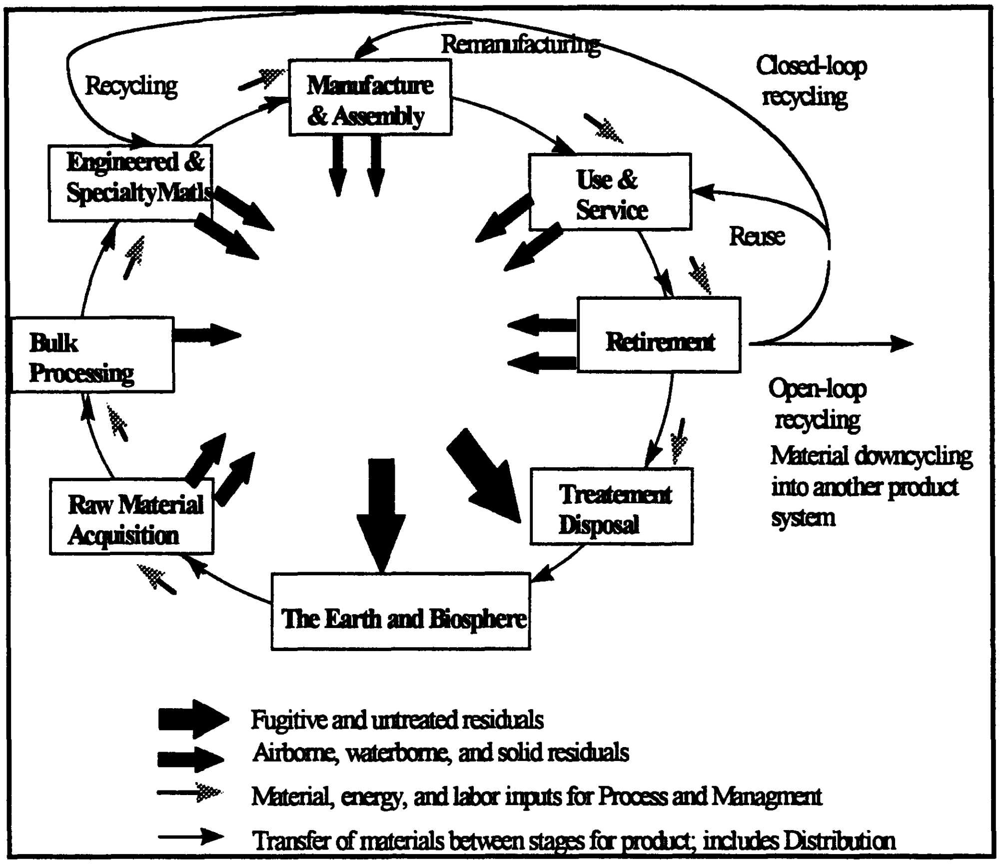

Figure 2.2: The Product Life Cycle System

DfE fundamentally deals with designing products and processes. The product or process design phase is where the critical decisions of a products characteristics are determined, and therefore the place where the most environmental improvements can be made. The product development cycle is a continuous process to meet customer needs, as shown in Figure 2-3. DfE is

[13] From "Life Cycle Design Guidance Manual - Environmental Requirements and The Product System", United States EPA, p.11.

a systematic approach that attempts to bring environmental concerns to the front end of the design process.

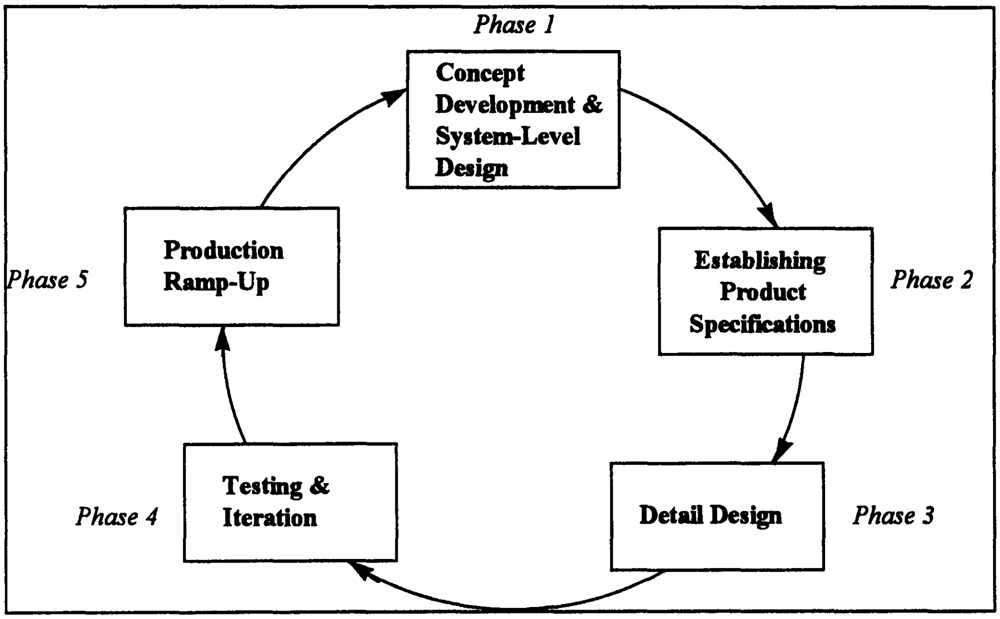

Figure 2.3: Generic Product Development Cycle

2.2 Importance of DfE

Gaining a competitive advantage in today's global marketplace requires greater speed in bringing products to market. This has been achieved in many firms through the adoption of concurrent engineering practices, which eliminate the barriers between R&D, engineering, manufacturing, and marketing. As environmental issues become an increasing concern, it is only natural that firms include DfE under the umbrella of concurrent engineering.

Despite the need to bring products to market with increasing speed, there are a number of factors that have generated an interest among manufacturing firms in adopting DfE practices[14]:

Customer awareness - Industrial and retail customers are increasingly concerned with the environmental performance of products, processes and suppliers.

A recent Gallup survey concluded that more than 75% of US consumers include environmentalism in their shopping decisions.[15] As a result, companies are recognizing the recent wave of ecological concern as more than a passing fad. Companies such as 3M have realized this early on and have adopted programs such as "Pollution Prevention Pays" back in 1975. 3M claims that its programs have saved $500 million and decreased air pollutants by 125,000 tons. These programs have resulted in 3M's reputation as a "green" company among consumers.

Regulatory pressures - Regulatory requirements for products and processes are increasing world-wide, especially in the area of product take-back and disposal.

In Germany, the landfilling of old automobile hulks and the shredder residues from automobile recycling operations is a growing problem. As a result, the German Government has proposed legislation that would require automakers to take back and recycle old automobiles at the end of their lifetime. This has stimulated German automakers, such as BMW and Volkswagen, to explore fundamental changes in automobile design that could result in more efficient materials management[16].

[14] Adopted from Electronic Industry Roadmap, MCC, p. 18.

[15] Kleiner, Art, "What Does it Mean to be Green?", Harvard Business Review, July-August 1991.

[16] "Green Products By Design," Office of Technology Assessment, 1992.

BMW recently built a pilot plant to study disassembly and recycling of recovered materials. The goal is to learn to make an automobile out of 100 percent reusable/recyclable parts by the year 2000.

> Product Differentiation - If products are similar from a cost and performance standpoint, then a more eco-efficient product could effect a purchase decision.

The Body Shop, a UK cosmetics company, was able to differentiate its products from competitors partly based on the environmental consciousness of the company and its products. The products sold were all natural, sold in refillable containers and used bio-degradable packaging. A fundamental part of the Body Shop's marketing strategy is based on practicing environmental consciousness throughout its operations.[17]

> Cost savings - Products that incorporate environmental concerns can improve profitability by savings in production, disposal and other life-cycle costs.

A 1990 Wall Street Journal Article, provides several examples of companies that have made changes to its operations that have resulted in significant cost savings as shown in Figure 2-4.[18]

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[17] Source "The Body Shop International", Harvard Business School Case Study, 9-392-032, April 5, 1994.

[18] Naj, Amal Kumar. 24 December 1990. Some Companies Cut Pollution by Altering Production Methods. *The Wall Street Journal*, A.

COMPANY	OPERATING CHANGE	BENEFIT
AT&T	Redesigned circuit-board cleaning process	Stopped using ozone-depleting chemical, cut cleaning costs by $3 million annually
Clairol	Switched from water to foam balls to flush pipes in hair-care product manufacturing	Reduced waste water 70%, saving $240,000 annually in disposal costs
3M	Developed adhesive for box-sealing tapes that doesn't require solvent	Eliminated the need for $2 million worth of pollution control equipment
Polaroid	Streamlined photographic chemical plants	Cut waste generation 31%; and disposal costs by $25,000 a year
Reynolds Metal	Replaced solvent-based ink with water-based in packaging plants	Cut emissions 65%, saved $30 million in pollution equipment

Figure 2.4: Cost Savings from Pollution Prevention

> Eco-label programs - A number of eco-labeling initiatives have been established in various markets, the oldest one being the Blue-Angel standard established in Germany in 1978.

The Blue-Angel award is given to categories of products that meet certain criteria. Supporters of the Blue Angel scheme point to several successes: paint and varnishes that are low in solvents and other hazardous substances command 50 percent of the German do-it-yourself market compared with just over 1 percent in the 1970's; over the same period, emission standards for oil and gas heating appliances improved by more than 30 percent[19].

Probably, the most significant factor in firms adopting DfE practices is the realization that incorporating environmental concerns into products and processes can result in increased profitability. Designing products with

[19] Green products by Design, Office of Technology Assessment, 1991.

minimal environmental impact and reducing pollution at its source can result in reduced operating costs, and possibly even increased market share.

2.3 Trends in DfE Design Tools

Although DfE is still in its developmental stages, several types of tools have been developed to help incorporate the principles of DfE into the design process:

- **Checklists** - A checklist is generally used by engineers or environmental personnel. The focus may be a specific topic such as toxic material use or recyclability, or it may be general and cover a broad range of environmental topics. The checklist is usually used during product or process design.

  IBM Environmental Systems Engineering Checklist,

  [DFESH Implementation Strategy for Semiconductor Industry Draft, Environmental and Occupational Risk Management, September 1995]

  Raychem Corporation,

  ["A Practical, Customer-Oriented DfE Methodology," IEEE Symposium on Electronics & the Environment, May 1995]

- **Risk ranking tools** - These tools include any system, computerized or not, that scores or ranks materials and processes based on environmental parameters. These systems are designed to help select the best material or process alternative. Systems may calculate absolute scores, while others may calculate relative scores to compare several choices at one time.

  CARRI Tool,

[DFESH Implementation Strategy for Semiconductor Industry Draft]

- **Design reviews** - Design reviews are intended to ensure the incorporation of environmental concerns into the design process. In some cases, a checklist of environmental criteria must be completed before a design can proceed to the next step in the development process. In general, design reviews require the presence of an environmental expert to ensure environmental compliance.

  Xerox Environmental Design Review,

  [Azar et. al, "Agent of Change: Xerox Design-for-Environment Program", IEEE Symposium on Electronics & the Environment, May 1995]

  DfE at Raychem,

  ["A Practical, Customer-Oriented DfE Methodology", IEEE 1995]

- **Life cycle assessment tools** - LCA is the process of evaluating the environmental impact of a product across all life cycle stages. According to SETAC[20], LCA consists of three main stages: inventory analysis, impact assessment and improvement assessment.[21] Most LCA tools focus on the inventory analysis stage, which is a description of the materials and energy flows into and out of the system. Some tools incorporate impact assessment, which is the process of evaluating the potential environmental effects associated with the materials and energy identified in the inventory analysis stage. The improvement step is the process of improving the identified environmental burdens. A limitation is the data requirements of a comprehensive LCA which can be quite challenging. The problem is where to draw the boundaries of the

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[20] SETAC (Society of Environmental Toxicology and Chemistry) is a professional society of 2,000 members founded in 1979 to provide a forum for individuals and organizations involved in the study of environmental problems, management and regulation of natural resources, research and development, education and manufacturing and distribution. It is the only professional organization that brings together environmental scientists and engineers from academia, government, industry and public interest groups to work on environmental problem solving. The forum is provided through meetings, publications and workshops.

[21] "A Technical Framework for Life-Cycle Assessment", SETAC, Pensacola, FL. January 1991.

analysis. Can specific materials and energy flows be ignored, without missing some environmental effects?[22]

Simapro,

[PRe Consultants, November 1995]

EcoSys,

["EcoSys - Supporting Green Design Through an Extensible Life Cycle Analysis Approach", Sandia National Labs, Albuquerque, NM. June 1995]

- **Cost accounting tools** - Tools developed to help track environmental costs that may previously have been unaccounted for, hidden, or considered to be non-quantifiable. Environmental cost information can be used to help communicate to customers or regulators genuine efforts at waste minimization and pollution prevention, as well as analyzing the financial effects of product or process design changes.

  Xerox - Finance Tool,

  [Azar et. al, "Agent of Change: Xerox Design-for-Environment Program", IEEE 1995]

  Integrated Life-Cycle Cost Assessment Model,

  [Warren, J.L. and Weitz, K.A., "Development of an Integrated Life-Cycle Cost Assessment Model", IEEE Symposium on Electronics & the Environment, May 1994]

These tools represent a wide array of approaches to DfE. The tools differ in terms of who uses the tool, where in the design process the tool is used and what type of information the tool provides. The challenge for companies is to determine which tools will be useful and how to get the tools implemented and in use.

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[22] Green Products by Design, OTA, p61.

2.4 Development of DfE Management Systems

The Environmental Management System (EMS) has been identified by the International Standard Organization (ISO) as "the organizational structure, responsibilities, practices, procedures, processes and resources for implementing and maintaining environmental management" (ISO 14001). EMS provides a foundation for implementing DfE system elements. EMS is a framework that can help to determine where DfE tools and practices can be successfully implemented within an organization to support company environmental goals.

A well-developed EMS addresses all levels in the company, providing a common vision for DfE activities. An EMS typically consists of an environmental policy and a well-documented program with goals and objectives. A fully developed EMS has all customers, suppliers, and employees involved in the environmental management program.

There are several examples of Environmental Management Systems that have been developed or are being developed by individual companies, industry groups, and government organizations. The management systems appear to vary in scope and specificity. The industry group and government EMS tend to be more general in nature providing guidelines and principles. The specific company EMS's seem to provide a more comprehensive and integrated approach that provide such things as: detailed guidelines for integrating environmental concerns into the company's development process, tools to support design teams and/or measurement systems to assure that progress is made.

The ISO 14001 is an example of an EMS developed by the International Standard Organization. The concept of the ISO 14000 EMS is to provide a framework for companies on which to base their company's EMS. The standard requires a policy statement, management commitment, training, continuous improvement of the management system, identification of environmental impacts, setting of environmental objectives and targets, and compliance with applicable regulations (ISO 14001 Draft, 7/13/94). This standard helps to provide a consistent basis for evaluating corporate environmental management systems. However, ISO 14001 does not contain specific tools applicable to a particular organization or industry.

The Global Environmental Management Initiative (GEMI) is an effort by a group of twenty-seven companies to address some of the concerns for developing an environmental management system. The twenty-seven companies include representatives from the chemical, pharmaceutical, and semiconductor industries. GEMI focuses on the concept of Total Quality Environmental Management (TQEM) as a method to achieve environmental improvement (GEMI TQEM Primer, 1993). The reason for TQEM is that it provides a familiar framework for incorporating environmental management issues into a quality-related system. GEMI promotes 16 International Chamber of Commerce (ICC) principles for achieving environmental excellence, such as: corporate priority of environmental management, environmental considerations in design and operation, prior assessment of environmental impacts, and employee education.[23] These principles are a beginning towards providing a framework for environmental management.

An example of a successful company EMS is Xerox's Environmental Leadership Program.[24] The program is a well developed system that has as its goal developing "waste-free" products. Xerox has incorporated environmental concerns into the early stages of its product development process. This has been accomplished by a change in product development procedures to include environmental design reviews at specific points within the development process. The reviews include a set of criteria that must be met in order to move to the next stage in development. In addition, Xerox has developed specific tools (financial model, design guidelines and standards, design for assembly software) to enable their strategy and support the design process.

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[23] GEMI, 1994. Environmental Self-Assessment Program, First Edition, November. Washington, D.C.

[24] "Agent of Change: Xerox Design-For-Environment Program", IEEE International Symposium on Electronics in the Environment, May 1995. Orlando, FL.

PROGRAM PHASE	CONCEPT EXPLORATION	DEMONSTRATION/ VALIDATION	ENGINEERING& MANUFACTURING DEVELOPMENT	PRODUCTION & DEPLOYMENT	OPERATION & SUPPORT
DfE RELATED TASKS	• HAZMAT Definition •Requirements Development •Supplier Mgt. Plan	•HAZMAT Mgt. Analysis •Supplier Requirements Flowdown •Material Team Planning •Supplier Mgt. Plan	• HAZMAT Mgt. Plan •Parts & Process Selection Guidance •Field Test & Maint. Considerations •HAZMAT Evaluation Env. Assessment •Design Reviews & Checklist •Production Readiness Review •Supplier Mgt. Plan	•HMMPS Update •HAZMAT Mgt.& Monitoring •Procured Mat'l Assessment •Production Checklist •Supplier Mgt. Plan	•Demil/Disposal Activities •Inventory Planning •Pack/Ship/Scrap Considerations •Facilities Deactivation •Site Cleanup •Others

Figure 2.5: Integrating DfE into the Product Development Process

Another example of an EMS is at Texas Instruments' Defense Systems and Electronics Group (TI-DSEG). The purpose of this program is similar to other EMS, as it is an initiative to institutionalize the systematic consideration of life cycle environmental concerns and decision-making in its product development and management process.[25] The success of this EMS is based on its foundation in TQM and the fundamental changes in its design process to include specific environmental tasks as shown in Figure 2-5[26]. TI-DSEG created DfE champions within the organization and then required that these subject matter experts participate in various product development projects. The results of this program has been the selection of more environmentally-friendly material, process, and technology alternatives. Examples include: the

[25] "Design for the Environment a Texas Instruments' Defense Systems and Electronics Group", IEEE Electronics and the Environment Symposium, May 1995. Orlando, FL.

[26] Ibid.

switch to powder paints (resulting in reduced VOC emissions and contaminated waste) and the substitution of stainless steel for cadmium-plated components.

The purpose of describing these environmental management systems is to provide an awareness of the range of systems in use. As companies such as Xerox and TI appear to have successfully integrated their environmental systems, it is important to understand how this was done and to provide a common framework so that these concepts can be transferred across companies. Many of the tools and processes used by the companies do not necessarily need to be company or organization specific. In many cases, the companies will benefit from coordinated efforts such as the GEMI and ISO 140001.

2.5 Summary

This overview of DfE provides us with some knowledge of the variety of DfE tools and management systems in existence. As DfE is a relatively new field of study, concepts, tools and management systems are constantly being changed and developed This makes it difficult to keep up with all the activities within the companies, governments and academia. However, the background provided here provides an acceptable basis for examining the DfE activities within two large manufacturing firms as we do in the following two chapters.

3. DfE at Motorola and United Technologies

3.1 Introduction

In order to gain a better understanding of how DfE is practiced in industry, we conducted an investigation of two large manufacturing firms: Motorola and United Technologies. The main purpose of the study was to learn about the various approaches to DfE at each company, and to identify areas for improvement.

Motorola is divided into six different sectors and UTC is divided into six different companies. Due to the decentralized nature of the corporations, we focused our investigation at the sector/company level. Our research included case studies of several sectors and companies that employ DfE activities and participation in several DfE projects.

The case studies included interviews with key personnel involved with DfE efforts. We interviewed product managers, designers, environmental engineers and technologists from across the companies to ensure a well-balanced view. A brief description of the Motorola and UTC sectors and companies we focused on are described in Appendix I.

Our involvement in DfE projects included working with several product teams to better understand the development process and how to incorporate environmental concerns into the design process. In addition, we participated in a DfE tool development effort and gained insight into the issues companies face in developing customized DfE tools (see Appendix II for more detail).

In this chapter we provide an overview of our discoveries. Specifically, we provide a summary of the various activities we observed across the companies.

3.2 Drivers for DfE Development

As we mentioned in Chapter 1, there are several factors motivating manufacturing firms to begin adopting DfE practices. At Motorola and UTC, we found that two dominated:

1. Increasing customer awareness
2. Changing regulatory pressures

Although there are other factors, these two factors are the main driving forces for DfE implementation, at these two companies, at this particular time.

3.2.1 Increasing Customer Involvement

The recent Brent Spar controversy highlights the fact that the consumer is increasingly aware of the environmental implications of their purchase decisions. More importantly, this incident points out the potential market power that can be brought to bear against companies who's activities are deemed "non-green" by the general public.

The Royal Dutch Shell Oil company was scheduled to dispose (at sea) of its abandoned Brent Spar platform in June of 1995. A Greenpeace organized gasoline boycott, especially effective in Germany, resulted in a 30% decrease of sales for Shell.[27] Additionally, several Shell stations were firebombed or otherwise vandalized. Ultimately, the company was forced to abandon its dumping plan in favor of a costly land cleanup and disposal. The incident, combined with controversy surrounding their operations in Nigeria contributed to Shell being singled out as an environmental "bad actor," a label that had significant impact on its financial performance.

Despite (or perhaps because of) incidents like these, many companies are trying to adopt a more proactive approach toward environmental issues. The focus on environmental issues is occurring throughout the supply chain from chemical supplier to manufacturer to the end customer. Within the automotive industry, for example, United Technologies recently organized a training session on DfE approaches. The Big 3 OEM's were each represented along with engineers from across UTC's automotive and research organizations. Each of the automakers

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[27] Leon Mangasarian, Brent Spar victory as Germans race down highway with no speed limit, Deutsche Presse-Agentur, June 21, 1995,

was given a chance to discuss their approaches and specifically what they would be expecting from their suppliers. Interestingly, although each of the automakers stated that environmental performance would be considered, none was prepared to admit a willingness to pay more for "greener" components.

Perhaps a more concrete motivation than end customer interest is that several OEM's are beginning to make specific environmental demands of their suppliers. At Motorola, several automotive customers have made requests that specific chemicals and materials not be used in a product. "Black listed" materials include:

- Lead
- Polychlorinated Biphenyl's (PCB's)
- Cadmium

These types of requests have pushed Motorola to put in place programs that not only meet these specifications but also help to identify and exceed future customer needs. As environmental requirements increase, Motorola hopes to remain slightly ahead of both the regulations and its customers.

Likewise at United Technologies, customer requirements increasingly stipulate the environmental features of products. This means that DfE policy and approaches are being set by some customers. Some examples include:

1. Hamilton Standard - was asked by the United States Air Force to catalog the material content of an engine controller so that the major components could be more completely recycled.
2. Sikorsky Aircraft - was awarded a $2 million extension to its Commanche Helicopter development program. The contract was to identify the material content of the craft and to specifically identify hazardous material.
3. Pratt and Whitney - the US Air Force has specified that the new engine for the F-119 not contain any lead, cadmium or asbestos.
4. UT Automotive - a wiring system was modified to meet the requests of Saab, Volvo and Rover that they not contain any PVC tape.
5. Carrier - the company was asked by one of its large, retail customers to consider selling "conditioned air" rather than air conditioning equipment. The first such extension of the product take back idea.

However, UTC is trying to go beyond satisfying specific needs. They also want to develop tools and approaches that move beyond customer requirements and allow a more comprehensive, UTC-wide DfE strategy that integrates DfE into everyday design practice. The corporate environmental group, United Technologies Research Center, and a company wide Pollution Prevention Coordination Team are working together toward this end.

3.2.2 Changing Regulatory Pressures

Traditionally, national governments have attempted to regulate the environmental effects of industrial companies primarily by controlling the manufacturing processes themselves and their undesired byproducts. Governments did this through "command & control" air, water and waste legislation.

Several governments, particularly in Europe, have begun experimenting with new forms of regulation that focus on the intended results of the manufacturing processes - the products.[28] (Figure 3-1)[29] There are several reasons for the move towards product regulation. Some of the product regulation is due in part to "reaction to unpleasant manifestations of the consumer 'throwaway society.'"[30] Another reason for the product regulation is the perceived failure of traditional command and control environmental regulations and the lack of consistent enforcement in many European Countries.[31]

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28 Hunter, Rod, "European Electrical and Electronic Product Take-Back Regulation", Bureau of National Affairs, June 14, 1995.

29 Adopted from Table 5-1 of US Congress, Office of Technology Assessment, ***Green Products by Design: Choices for a Cleaner Environment***, OTA-E-541 (Washington, DC: US Government Printing Office, October 1992.

30 Hunter, Rod, "European Electrical and Electronic Product Take-Back Regulation", Bureau of National Affairs, June 14, 1995.

31 Hunter, Rod, "Missing Links in the Chain of European Law," Wall Street Journal Europe, April 10, 1995.

Economic Commission for Europe (United Nations)

A task force is developing guidelines for "environmental product profiles", a qualitative description of the environmental impacts of a product for use by commercial and institutional buyers.

European Community

Draft law requiring specific percentages of recovery (recycling, incineration, and composting) for product packaging.

EC Eco-label.

Denmark

Ban on domestically produced non-refillable bottles and aluminum cans.

Fee imposed on waste delivered to landfills and incinerators as an incentive to recycling and to support clean technology

Germany

Packaging Waste Law, passed in 1991, gives manufacturers responsibility for collecting and recycling various kinds of packaging at specified rates by certain dates.

Manufacturer take-back-and-recycle laws have been proposed by the government for automobiles, electronic goods, and other durables.

Japan

Recycling Law, passed in 1991, sets target recycling rates around 60 percent for most discarded materials by the mid-1990s. Includes product redesign strategies for packaging and durable goods.

Netherlands

National Environmental Policy Plan sets national targets and timetables for implementing clean technology, including redesign of products.

Figure 3.1: Examples of Product Oriented Environmental Policies

The product regulation in Europe has taken the form of direct regulation regarding, for example, product-content (substance restrictions and bans) and "eco-taxes." European governments have also been experimenting with "take-back" schemes to extend manufacturers responsibility to the end of the products useful life. In addition, the European Union is beginning to consider the merging of environmental laws in Europe, however, it is still unclear how soon this will take place.

Germany led the way in 1991 with regulation requiring "take-back" of packaging waste. One example is the Eco-Waste Law which comes under the heading of "producer responsibility". The law explains that this broad notion of "producer responsibility" is to include in particular[32]:

- Development, manufacture, and distribution of reusable or long-life products;
- Use of recyclable waste or secondary raw materials for production of products;
- Labeling of dangerous substances in products to facilitate safe waste management;
- Labeling products with regard to their reusability, recoverability, take-back, and deposits; and
- Product take-back and recovery obligations.

The law provides the government with the authority to promulgate these regulations, translating these broad objectives into specific obligations for manufacturers.

These policies of other nations are significant to the US. First of all, these policies affect the international market in which US goods compete. The success of US companies may depend on their ability to develop successful approaches to DfE. Second, these policies maybe viewed as giving domestic industries an

[32] Hunter, Rod, "European Electrical and Electronic Product Take-Back Regulation", Bureau of National Affairs, June 14, 1995.

unfair advantage. For example, Denmark's decision to ban the sale of beer in non-refillable containers gave an advantage to local producers who were quickly able to develop a system for non-refillable containers.[33] Foreign companies were at a disadvantage when attempting to establish such a system in a foreign market in a short period of time.

Motorola is beginning to feel these regulatory pressures through their customers in Europe. One of Motorola's Dutch customers recently made it clear that several environmental requirements need to be met in order to continue their purchase of certain electronic products. Their demands included:

- improved energy conservation
- different types of plastics are clearly labeled
- plastic materials can easily be separated
- the concentration of certain plastic additives be limited (e.g. cadmium is not present in any concentration higher than 50 mg/kg plastic)

These requirements are based on Dutch Environmental Policy, which is acknowledged to be the most comprehensive and detailed in the world.[34] In order to meet these requirements and compete in the Dutch marketplace,

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[33] Ibid., p.67.

[34] Environmental Resources Limited, Environmental Sound Product Design: Policies and Practices in Western Europe and Japan, July 1991, p.22.

Motorola understands the need to consider the issues early in the design process. Consideration of these requirements after the product is designed and manufactured is no longer sufficient.

Companies are realizing that they will need to comply with a number of environmental policies, in order to compete in a global marketplace. Currently, the take-back legislation proposed in Europe is forcing manufactures to consider recycling, re-manufacturing and disassembly issues as the legislation requires manufacturers to be responsible for their products at the end of its life. At Motorola, they have developed a take-back task force in order to deal with these issues. The group is composed of high level managers from each sector. The task force is responsible for developing strategy and technologies to respond to the proposed legislation. United Technologies is considering product take-back as part of a comprehensive look at DfE and the ISO 14000 environmental management standards.

3.3 Approaches to DfE

As environmental customer needs and regulatory pressures have increased at Motorola and UTC, both companies have begun to engage in activities that they refer to as DfE. These activities can be grouped into the following categories:

- Design guides

- Design reviews
- Life cycle analysis
- DfE management systems

The following section provides specific examples found within the various sectors and companies of Motorola and UTC.

3.3.1 Design Guides

Design guidelines are similar to the checklist described in Section 2.3. Design guides provide suggestions to designers for environmental design improvements. A checklist is a specific example of a design guide that requires a specific criteria to be met.

United Technologies' Hamilton Standard uses a guideline referred to as Technical Standard 0300 (TS0300) (see Figure 3-2). The standard is a material and process substitution guideline intended to help designers minimize the generation of wastes on the EPA 33/50 list. The guidelines include a list of commonly used process and material specifications that should be avoided. The guideline also suggests environmentally friendlier replacements for processes that are often used. TS0300 has also been successfully transferred (with slight modification) within United Technologies to Pratt and Whitney. This is one of the few examples that we observed of this type of DfE system or tool sharing across company or sector boundaries.

Cadmium Plating: (MIL-C-8837, AMS 2400, AMS 2401, QQ-P-416)
New parts shall not be cadmium plated. This includes all standard parts plated by electro-deposition. Alternatives to cadmium plating include:

1. Use of corrosion resistant steel
2. Use of other coatings such as aluminum ion vapor deposition (MIL- C-83488)
3. Use of paint in place of plating
4. Use of metallic-ceramic coating such as MIL-C-41245
5. Use of nickel plating to provide an inherent barrier

Chromium Plating: (AMS2406, AMS2407)
Chromium plating is used for wear and anti-fretting. Alternatives include:

1. Electroless nickel
2. Gas nitriding
3. Hard facings such as plasma sprayed chromium oxide which are currently virtually interchangeable with chromium plate on aluminum butterfly valves.
4. Titanium nitride or other vapor deposited coatings
5. Wear resistant materials such as AISI 440C or CPM 10V
6. Hardcoat (MIL-A-8625 Type III, AMS 2469) for aluminum

Figure 3.2: TS 0300 Example

At Motorola, one sector recently developed design guidelines for environmentally preferred radio products. The purpose of the guidelines is to help Motorola consider the impact of their products on the environment and the costs associated with the end of the product life cycle. The guidelines are broken down into three main sections:

1. Restricted substances
2. General design guidelines
3. Component specific guidelines.

The restricted substances section is intended to address material toxicological impact. By listing internally regulated materials, their common applications, and less hazardous alternatives, this section provides information that is useful to designers wishing to reduce the use of toxic materials.

The general design guidelines section provides suggestions to enhance reclaim and/or minimize environmental impact, as they specifically relate to electronic products.

The final section, the component specific guidelines, compares performance characteristics for a number of subassemblies using environmental impact and de-manufacturability considerations. These environmentally preferred guidelines for radio products have just recently been developed, and are currently being reviewed within several product groups.

A more sophisticated design guideline under development at Motorola is the Design Advisor (DA). This tool is based on the Tiered Methodology[35] and the component specific guidelines described above. Both of these concepts focus on providing designers with guidelines to use in early stages of product development. The DA focuses on product design at the component level or detail design phase of product development. The initial components selected for developing this tool were based on typical contents found in a radio product, as these components are fairly common across the company.

The basis of the tool is a database of materials and processes that a designer can choose from to "create" a part. Each material and process is assigned a score which measures its environmental impact relative to other materials and processes in the database. The impact areas are determined by the company depending on corporate requirements and customer needs. For example, in this case toxicity and energy use are two impact areas that have been selected. Each impact area has metrics which attempt to relate the approximate effect the materials and processes of a component have on an impact area. These metrics are translated to a scoring system that provides a score for each material and process. These materials and processes are then combined to provide an overall component environmental score. Assigning a score allows the direct comparison

[35] Hoffman, Bill, "A Tiered Approach to Design for Environment", Clean Electronic Products and Technology IEE Conference, Edinburgh, Scotland. October 1995.

of two parts that may have different material content or use different processes. (Figure 3-3)

Shield No.	Description
1	stamped cold-rolled steel with nickel electroless-plating, reflowed on to board
2	die-cast zinc-aluminum with tin electroplating
3	injection-molded polycarbonate with copper and nickel electroless plating

	Materials	Mass	Sustainability	Toxicity	Energy	Overall Score*
Shield #1	cold-rolled steel	10	39	10	25.1	
	nickel (plating)	1	44.5	30	26.1	
impact score			39.5	11.8	25.2	**25.5**
Shield #2	zinc-aluminum	9	76.5	15		
	tin (plating)	2	68.5	20		
impact score			75.05	15.9	25.3	**38.8**
Shield #3	polycarbonate	15	90	20	50	
	copper (plating)	1	68.5	30	24.2	
	nickel (plating)	1	44.5	30	26.1	
impact score			84.4	16.7	45.9	**49**

*Note: Lower score is preferred.

Figure 3.3: Comparison Using The Design Advisor

The Design Advisor tool is still under development through the joint effort of several sectors at Motorola. For more detail on the development of this tool, please refer to Appendix II.

3.3.2 Design Reviews

The purpose of a design reviews as described in Section 2.3 is to check the progress of a product design project at specific points along the process. The goal is to leverage the collective experience of a large design team and insure that critical design requirements are appropriately considered. As part of this review process, some companies are now including environmental attributes.

Hamilton Standard's various engineering system manuals (ESM's) include requirements for environmental compliance reviews. The project engineer must perform the reviews at specified times in the design process and certify such standards as TS0300 (described previously) with his or her signature. There are several exceptions that are allowed for TS0300 certification.

1. The increased costs would make an existing product non-competitive
2. Design changes that involve no hardware changes (Software only)
3. The design is for development only, no production will follow
4. Replacements do not perform adequately to meet service or qualification requirements
5. New designs that incorporate previously designed sub-assemblies that do not meet TS0300.
6. The hazardous waste generating material/process is a contractual requirement.
7. Adequate waste treatment facilities are in place and there is no cost effective alternative.

The review process also requires that a tracking system be used to identify situations where TS0300 is not being met. Compliance tracking allows for training improvement, the prioritization of R&D efforts, and the investigation of possible alternative processes or materials. Additionally, it provides a metric that is useful for measuring the environmental improvement of Hamilton Standard's products. The TSO300 standard has been in use for several years although the tracking portion of the system has not been implemented and company wide training has not been given.

At Motorola, they have also begun to consider environmental issues during design reviews. Engineering design reviews are generally conducted after each significant phase in the development process as shown in Figure 3-4. Each review is conducted to ensure that specific technical requirements have been met. The requirement for ensuring environmental issues are considered is that the checklist for environmental concerns is reviewed, not necessarily that all the conditions are satisfied. The environmental review is usually performed after the design/prototype phase.

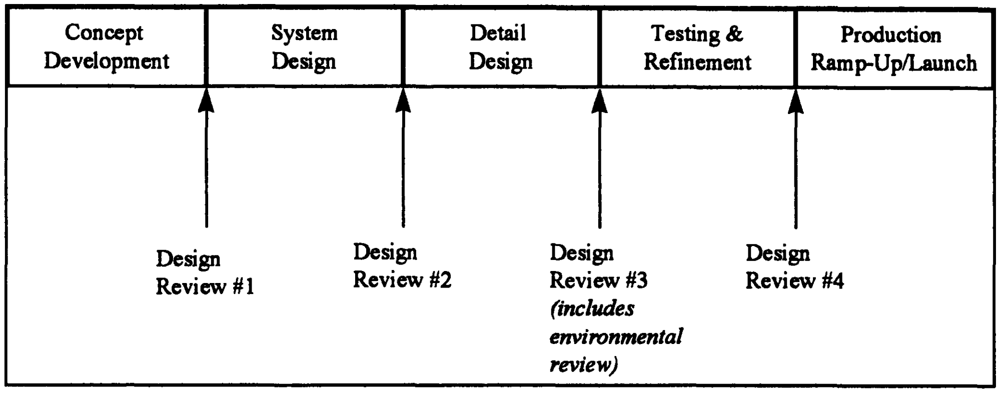

Figure 3.4: Product Development Process Summary

However, in another part of the company an environmental expert is included as part of the design review process. In this case, design reviews are a forum to present a concept to an experienced, multi-functional group of engineers to get some feedback. By including an environmental expert in this process, Motorola hopes to identify areas where the product or process can be improved early enough that significant changes can be effected. This sector of Motorola is currently adding the environmental review to its official design review requirements.

3.3.3 Life Cycle Analysis

Life Cycle Analysis (LCA) is a tool for analyzing the environmental impact of a product throughout its life-cycle. The Life Cycle approach is practiced to gain a better understanding of the materials and processes that have the most significant environmental impact and room for improvements. As this process is quite data and resource intensive, companies are searching for ways to streamline the analysis or find better tools to help perform an LCA.

Motorola is using a life cycle matrix tool that is based on the Tier 1 phase of the Tiered Methodology. This tool is general in nature and is intended to call into question past design options and to direct the team toward new, environmentally preferred designs. The tool is designed to complement the early design phase of product development when little qualitative information is known about the design. The tool is a series of questions that are focused on addressing the stages in the life cycle which can reasonably be controlled by the design team. The stages of importance are Sourcing, Manufacturing, Transportation, Use, and End-of-Life. This abridged life cycle defines the sphere of influence in which Motorola works.

The questions are focused on the various impact areas that each life cycle stage affects. The impact categories are a variation of the following goals,

1. Minimize Resource and Energy Use
2. Minimize the product's impact on Human and Ecological Health

Using the impact categories as rows and the life cycle stages as columns a matrix can be formed. For this Tier 1 matrix each of the matrix elements consists of four questions which have a yes or no answer. Each yes answer is a 1 and no answers are given a 0, then points are summed to give a score for the matrix element (see Figure 3-5[36]). These scores can be summed to provide an overall product. The results of this tool are used to identify areas of opportunity for improvement in the current product concept. This tool has been used by several product groups within Motorola and has resulted in suggestions for improvement in subsequent designs.

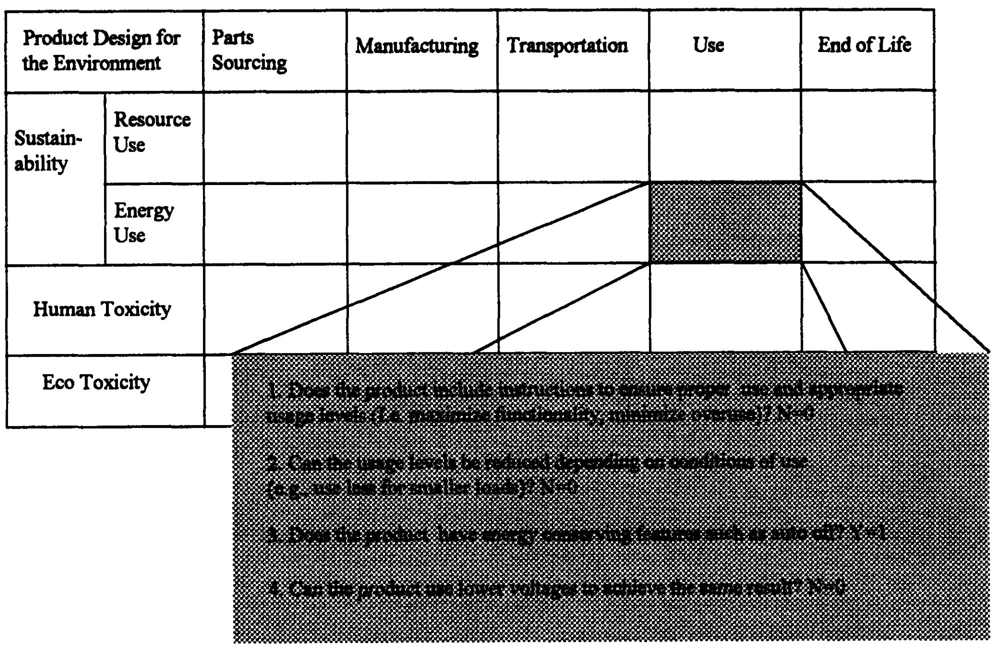

Figure 3.5: Tier I Life Cycle Matrix

UTC is currently testing the use and implementation of a different LCA tool - SimaPro software. The software provides a way to capture, analyze and present life cycle data to a designer. The first application of this software is an effort lead

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[36] Hoffman, Bill, "A Tiered Approach to Design for Environment", Clean Electronic Products and Technology IEE

by the United Technologies Research Center and the Automotive group in Europe. The project is focusing on automotive wiring harnesses and on educating the design centers in the use of the software. There is substantial information[37] available on this leading edge effort.

At Motorola, the Corporate Environmental Technology Group is just beginning to perform LCAs on selected products. They are in the process of learning how to compile the inventory stage of an LCA for a base station unit following the approach recommended by SETAC. This effort represents one of the first attempts by an electronics manufacturer to perform an LCA on one of its more complex products.

3.3.4 DfE Management Systems

DfE management systems are a combination of policy and tools designed to address different needs during the product development process. DfE systems can be used by designers, managers or environmental personnel depending on the specific need.

An example of a DfE management system is the Tiered Methodology, currently under development at Motorola. The tiered methodology is based on the

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Conference, Edinburgh, Scotland. October 1995.

[37] Rimawi, Ennis, "The Development and Introduction of Emerging Environmental Design Tools to Provide a Differentiating Capability for an Automotive Supplier," MIT Master's Thesis, June 1996.

product development cycle and is structured to reflect the varying amount of information that is available during the different phases of product design. In the early stages of design, a general concept is laid out leading to design rules and specifications. These specifications provide information that can be used to understand the environmental implications of some choices (Tier 1: Concept Development). Later, when specific components of the product are designed, questions about the material and manufacture of the part are asked (Tier 2: Detail Design). In the end, when the final design is complete, a thorough evaluation of the product is possible (Tier 3: Full Product Assessment). A more detailed description of the tiered tools is given below.

> Tier 1: Concept Development- At this stage in product development, the product is just a concept. The concept is usually not very well-defined, but there is an opportunity to make environmental improvements. This is the stage when specifications and design goals are set. The Tier 1 tool is general in nature, focused on questioning prior design choices and directing the team towards new, environmentally preferred, design options. A tool for this stage has been developed and is based on a series of questions asked about the various life cycle stages (material, manufacturing, transportation, use and end of life) and their impact (resource use, energy use and toxicity) on the environment.

> Tier 2: Detail Design- At this stage, the product components are designed and specified in detail. Here the material choices and manufacturing process choices are being made. A direct comparison is made between various component designs, such as the use of one material over another. The design at this stage, is focused on individual parts in isolation of the whole product. The design tool for this tier is focused at component design such as EMI shields, batteries, displays etc. A tool for this stage is currently under development at Motorola, see Appendix II for details.

Tier 3: Full Product Assessment - At this stage, the full product is developed and a complete product assessment can be performed. Once the product is manufactured, information about the manufacturing processes, disassembly time and material composition can be determined. Absolute values of energy use, waste generation and virgin material use can be used to evaluate products rather than the relative comparisons used in Tier 2. This full product assessment is similar to what is traditionally referred to as a life cycle assessment. A Tier 3 tool is currently in the initial stages of development at Motorola.

Another example of a DfE management system are the tools being developed by Motorola's Semi-Conductor group in collaboration with SEMATECH[38]. These tools are aimed at helping designers in the U.S. and Europe reduce the environmental impact of the processes used in manufacturing semiconductor products. The tools are described briefly below.

CARRI: Risk Assessment Model - CARRI is a computerized risk ranking tool that provides a consistent method for engineers and managers in the semiconductor industry to evaluate alternative chemicals and processes to determine their relative ESH impacts. The tool evaluates the risks by assessing both the inherent hazard properties of the chemicals and the potential for exposure to the chemicals. The relative impact of each process is determined using the Analytical Hierarchy Process[39]. The tool is available with a standard set of pre-defined semiconductor manufacturing processes with the ability to define more in the future.

Cost of Ownership - This accounting tool provides the framework for accounting activities that drive ESH costs at the manufacturing process level. This refers to accounting for direct and indirect costs, as well as

[38] SEMATECH is a partnership of semiconductor manufacturers which include companies, such as Motorola, Texas Instruments, IBM, AT&T, Digital and Rockwell.

[39] Saaty, Thomas L., The Analytic Hierarchy Process, New York: McGraw Hill, Inc., 1980.

tangible and less-tangible costs. This model not only accounts for traditional materials and operating costs but also hidden costs such as ESH management costs and cost benefits from recycling and energy efficiency improvements. Although the model is robust, there is still some difficulty in estimating some of the less-tangible costs. The model is best utilized by technical staff who are aware of ESH problems but are unsure of the magnitude of the economic impact. This tool is developed specifically for SEMATECH member companies.

Materials/Energy Balance - This tool will allow an engineer to complete a mass energy balance at the process and factory level. The user will provide specific input information, and the tool will determine the process output (or emissions). The model will help to track total emissions of a compound in the facility for permitting purposes or waste generation information. This tool will be available for SEMATECH members in 1997.

Abridged Life Cycle Assessment (ALCA) Matrix - The matrix tool is based on the Tiered Approach developed by the Corporate Manufacturing Research Center at Motorola. The tool enables a semi-quantitative life cycle assessment without having to complete a life cycle inventory and assess each and every ESH concern. The process matrix is designed to assist in the evaluation of materials choice, energy use, solid residues, liquid residues and gaseous residues for various life cycle stages. This tool will be beta tested in the near future.

The goal is to eventually link all of the materials/energy balance and Cost of Ownership models with the CARRI risk assessment tool to provide a more robust tool. This integration of the tools will facilitate a complete ESH evaluation of design alternatives by allowing the tools to share data and perform evaluations simultaneously. The ALCA Matrix will provide process engineers an overall assessment tool that can be used during the various phases of process development.

3.4 Summary

Based on the survey, we observed that between these two firms there are many approaches that are referred to as "DfE". The term DfE appears to have a very broad definition and is interpreted by different businesses to mean different things. In the following chapter we provide an assessment of general DfE approaches including our findings at Motorola and UTC.

4. DfE Assessment

4.1 Introduction

In this chapter we assess the DfE activities of Motorola and UTC and comment on the general approaches that are used. The assessment is based on our interpretation of DfE as it is presented in the literature by academics and practitioners (Chapter 2 - DfE Overview) and our own observations and experiences. The assessment focuses on the four DfE activities presented in Chapter 3:

1. Design guides
2. Design reviews
3. Life cycle analyses
4. DfE management systems

Specifically, we examine the benefits and specific areas of concern for each DfE activity both at the companies and in general.

4.2 Design Guides

4.2.1 Benefits

The development and use of design guides is the DfE activity most commonly used by Motorola and UTC. There appear to be two driving factors for this focus on design guides:

1. The ease of use by the designer
2. The ability to address specific customer or regulatory concerns

The design guides are usually presented as list of *do's* and *don'ts* for the designer (see Figure 3-2). For example, the TS-0300 standard lists materials and processes to avoid and suggests alternatives. This type of guide is easy for the designer to check and incorporate into his or her design work and requires minimal training.

In addition, these guides are based on specific customer and regulatory concerns. Therefore, the designer has the ability to address environmental concerns of customers during the design process, rather than after the product has been designed. For example, the guidelines for Environmentally Preferred Radio Products includes a "hot list" of materials that Motorola customers would prefer to avoid. TS-0300 is based on the EPA's 33/50 list. These guides provides an efficient way to keep designers informed of such external concerns.

Motorola and UTC have realized several benefits from the use of design guides:

- Improved information sharing across the company
- Thorough information in the specific areas the design guides cover
- Provides a good "starting point" for designers in addressing environmental issues

These features aid in incorporating the principles of DfE into the company culture.

Design guides tend to address customer and regulatory concerns that are shared across the company and are simple to understand, therefore, they can easily be shared. For example, the TS-0300 standard developed at Hamilton Standard has been adopted by Pratt and Whitney. The Design Advisor is being developed jointly among several sectors at Motorola. This sharing of information provides learning from one sector to another and an economies of scale in development. It also helps the company to address environmental concerns uniformly and consistently.

As design guides are generally developed to meet specific concerns, they tend to be very thorough in the areas that they address. For example, the Design Advisor focuses on specific components, and the components studied are presented in great detail. For the EMI shield components, there is information on the material and processes of a large number of shields that are used within Motorola. This type of thoroughness provides the designer sufficient information to evaluate the difficult tradeoffs.

Finally, the design guides are a good way to introduce designers to the environmental impacts of their products. Designers want to address these concerns and need some guidance, but they do not want a complex system that interferes with the development process. Designers currently use a number of different tools to help with the design process. Computer Aid Drafting (CAD) tools are used for mechanical design, Design for Assembly (DfA) software helps reduce the product's part count, and spreadsheet models track the costs. Designers are reluctant to add yet another constraint or yet another piece of software to their already complex design environment. Until a highly integrated DfE tool is available, design guidelines provide an easy "first step" for designers.[40]

4.2.2 Areas of Concern

Although the design guides provide several important benefits, they also have some important deficiencies:

- Focus on only a small number of life cycle stages and impact areas
- Compliance auditing is rare or nonexistent
- Not well integrated into the product development process
- Fail to provide a mechanism for continuous improvement

As mentioned previously, the design guides do a satisfactory job of thoroughly addressing certain, specific needs. However, the focus of the guides tends to be on the manufacturing and end of life stages of the product, other stages are ignored. The Design Advisor and TS-0300 both focus on reducing toxic material use during the manufacturing stage. This type of focus can lead to an improvement in one area

[40] This statement is based on interviews with over 20 designers within various sectors at Motorola and UTC.

at the expense of another. For example, using a plastic housing eliminates the need to use chrome plated metal. The result is a part that emits less hazardous material during its manufacture but will not be recycled. Which is environmentally superior? The answer is unclear at best.

Another issue with the design guides is that compliance is not tracked. The TS-0300 standard exists but there is no check that a product meets TS-0300 compliance, only that the standard has been reviewed by the design team. The tracking system that was developed has never been implemented. Compliance tracking is important for several reasons. First, it allows the design group to take credit for improvements that are being made. This is important if environmental performance is ever to be viewed as a competitive item. Also, it identifies areas where progress is not being made so that additional resources can be allocated as necessary. Tracking information is even useful for establishing R&D priorities and justifying spending.

In practice, the guides are just one of many pieces of paper that the designers must review. They are not integrated with the Computer Aided Design Systems, which are used by the designers on a frequent basis. The guides are not easily accessible to the designer during development and are not a part of their normal "toolkit". Moreover, the design guides are not an integral part of the product development process but are mostly a formality completed after the design is finished. Although this may seem like a trivial problem of implementation, we believe that the "convenience factor" can determine whether a design guide becomes a useful DfE tool or a largely symbolic gesture of environmental activism.

Design guides tend to focus on certain specific suggestions - a checklist of materials and processes. This format does not stimulate new ideas. A suggestion that Material A is an environmentally superior substitute for Material B will result in a series of designs that merely exchange Material A for B. This amounts to picking the low hanging fruit of DfE and will not lead to long term, continuous improvement. Clearly, a more comprehensive, integrated DfE approach is needed for that type of improvement to occur.

4.3 Design Reviews

4.3.1 Benefits

The implementation of environmental design reviews that incorporate the design guides have not only the benefits provided by design guides but also the additional benefits provided by design reviews. One or two groups within Motorola and UTC have recently begun to make this transition, and received the following additional benefits:

- The formal integration of environmental concerns into the design process

- The consideration of environmental constraints along with more traditional constraints such as cost, quality and functionality

The integration of environmental concerns into the design process is a fundamental part of a sound DfE system. This allows environmental concerns to be considered at several points during the development process, which forces environmental requirements to be considered earlier in the design process, before all the critical design choices are made. For example, using the Tier 1 design tool as part of the design process helped a product development team realize that switching from aluminum and plastic to aluminum only would result in a more recyclable product. This realization allowed the team to adjust its marketing campaign before it had been finalized. The team also found that adding the Tier 1 tool to their existing design process did not significantly disturb it. They found the change to be much easier to adapt to than an entirely new design system.

Another benefit of design reviews is that environmental considerations are made along with cost, quality and functionality considerations. This makes it easier to appreciate the tradeoffs that are being made when certain materials or processes are chosen over others. A design team at Motorola that has environmental "experts" as part of the design review process was able to identify several opportunities to substitute hazardous materials and improve transport packaging. For example, one particular design expert was working with various divisions within the company and with suppliers to reduce transport packaging for products. Through his involvement with a design team, he was able to use his knowledge to reduce the packaging needed for a particular product while maintaining the needed protection for the product. In fact, he helped to develop a system with suppliers where the packaging was reused and/or recycled. Of course, the choices were made considering all of the various tradeoffs such as cost and functionality - not just environmental concerns.

4.3.2 Areas of Concern

Although there is added benefit to implementing design reviews, we are concerned with our experience as to the way the design reviews were conducted:

- environmental concerns considered last priority
- review is completed after key design choices are made
- environmental expertise resides only with "experts"
- focus on manufacturing and end of life

The introduction of environmental considerations in design reviews did not appear to change the fundamental way design teams viewed environmental concerns. Even though environmental concerns were considered during reviews, it was usually after all other concerns had been reviewed and satisfied (see Figure 2-6). At this point all the critical design choices are made and significant environmental improvements cannot be made very easily. (There are some cases where improvements are made, but these cases are few). What makes it difficult for design teams to consider environmental concerns is that there are usually no specific environmental goals during the requirements stage of the design cycle. Therefore even if design reviews are implemented the goals of the review are often unclear. In some cases there are several specific environmental criteria that the team must review but no indication of what the final goal is. In contrast, for technical reviews there are specific goals that the team is trying to meet. These goals are usually set early during the concept development phase.

A complaint among some designers we interviewed at Motorola was the lack of overall product goals that addressed environmental issues. In other words, although environmental reviews were conducted - there were no clearly defined environmental goals to be satisfied. Therefore, there was no way to ensure that environmental issues were actually being addressed and there was no incentive for designers to address these issues. The environmental review consisted of no more than a checklist of several materials and processes that should be avoided when designing new products. In order to fully integrate environmental issues into business practices, measurement techniques are important to ensuring standards and other requirements are adhered to. To ensure the effectiveness of these DfE systems, "meaningful performance measures need to be developed and rigorously applied on a systematic basis." [41]

The design reviews that we observed failed to consider issues outside of the manufacturing and end of life stages. In addition, the only impact areas considered were hazardous material content and emissions. This narrow focus only serves to reinforce the common mind set that those are the only issues of importance to designers.

While the practice of DfE is still in its infancy, the reliance on environmental experts is tolerable. However, if these considerations are truly to be made part of the design process then the environmental knowledge needs to be transferred within the individual design team members. Also, having an outside expert review a design for its environmental merits will not be very effective if the design team has already decided that the design meets all of their objectives. To have an integrative and functioning DfE process, designers need to gain an understanding of environmental concerns themselves, in order to balance them with other considerations. Without this transfer of environmental knowledge, it will be impossible to integrate DfE into the product development process.

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[41] Microelectronics and Computer Technology Corporation (MCC), *"Electronics Industry Environmental Roadmap"*, p. 18, Austin, TX. 1994.

4.4 Life Cycle Analysis

4.4.1 Benefits

Many companies, including Motorola and UTC, have employed life cycle analyses as a DfE activity for several reasons:

- to force consideration of all life cycle stages and impact areas
- LCA is the best known approach for quantifying environmental impact
- to leverage data from literature, public and commercial databases
- the existence of a framework for performing LCAs
- LCA makes it possible to discover the source(s) of a "bad" score (data transparency)

The defining feature of an LCA is that it forces the consideration of all life cycle stages and impact areas. For example, the Tier 1 matrix tool asks questions about manufacturing, use and end of life. This is in contrast to other DfE tools that tend to focus on only one life cycle stage such as manufacturing as in the TS-0300 guideline or disassembly in the RESTAR software package.

LCA tools such as SimaPro provide a quantitative analysis of the environmental impact of a product, using (in the case of SimaPro) an eco-point method for computing a "final score." This type of analysis and scoring is helpful for comparing various product designs are identifying areas for improvement. In addition, the rigorous approach and standardized data lend an air of credibility to the analysis that is missing from other approaches. Often, it is not until more research is done that this credibility is called into question.

When performing an LCA, specific and detailed data is necessary for the mass and energy balances associated with the products life. Currently, a limited amount of this data is available from a variety of sources for a variety of processes. As this type of information becomes more easily available it will make performing LCAs much easier. Some of the data sources currently in use are the Simapro tool and PEMS (Pira Environmental Management System)[42]. Both are commercially available and provide a database of information on the impact of certain processes and materials. The PEMS tool has four main databases: materials manufacture, transportation, energy generation and waste management. Another source of data on material properties are company specific databases. GE Plastics provides access to detailed information on its materials via the Internet on World Wide Web (http://www.ge.com). This type of access makes it very easy to collect needed information. Leading consulting companies provide reports and studies that can provide needed data on material or process impact. For example, a report by Franklin Associates Ltd.[43], one of the leading consulting companies for energy analysis and life cycle analysis, provides energy consumption data for a variety of

[42] Snowdon, Dr. Ken G., "Environmental Life Cycle Assessment of Face plates used in the Telecommunications Industry", International Symposium on Electronics and the Environment, San Franciso, May 2-4, 1994.

[43] Franklin Associates, LTD., "Comparative Energy Evaluation of Plastic Products and Their Alternatives for the Building and Construction and Transportation Industries, Final report to the Society of the Plastics industry, INC. " , Society of the Plastics Industry, Inc., 1991.

plastic and alternative materials. This is only a sample of the resources available to companies in collecting material and process data.

Finally, the most significant reason that LCA's have become accepted among firms is because SETAC (Society of Environmental Toxicology and Chemistry) has agreed to an overall framework for performing the inventory stage of an LCA. SETAC has brought various organizations together to agree on a framework for performing an LCA, so that there is some basis for comparing the results across (or within) companies. Research is currently underway to help advance the technical framework for the impact and improvement LCA stages as well.

4.4.2 Areas of Concern

Although LCA is an excellent way to quantify the environmental impact of a product, there are several concerns with their application within a company. Based on our experience with Motorola and UTC, we see several issues:

- Conducting a comprehensive LCA inventory is expensive and time consuming
- The available data sources vary in quality[44] and it is difficult to ascertain that variability
- The LCA requires specific environmental "knowledge" that is not possessed outside of the EH&S organization

[44] We define the quality of LCA process data as being measured in two parts, uncertainty and completeness. Uncertainty refers to the estimated range of the quantity being recorded. Completeness refers to the degree to which all relevant variables (e.g. emissions) have been accounted for. In this way, a process that has been modeled as only having one emission stream when, in fact, there are several, has a low "completeness" score. See later chapter 4 for more information.

- The LCA is performed after a product has been designed and the information is rarely carried forward to subsequent design teams

At Motorola, their work on the LCA of a base station unit has proven very resource intensive. After 8 person months of effort, they have been able to collect only 50 to 60% of the inventory data and components produced by outside suppliers have not been included at all. Most of the time has been spent locating information and then converting it to the correct format. For example, data on the waste streams is collected on a monthly, per plant basis rather than on a per product basis. Converting to the correct units is a difficult task that involves gross approximations and estimates. In other cases, the data is not available within the company but rather must be obtained from a supplier. Currently, suppliers are uncomfortable and sometimes unwilling to share this type of information for fear that it might be used as the basis for vendor selection. Oftentimes, they do not possess the necessary information and are not willing to expend the resources to gather it.

Although some data is available from public sources, the data varies in quality. None of the data sources we observed provided any more than a qualitative indication of the uncertainty associated with the data. For this reason, companies such as UTC and Motorola that rely extensively on such sources have no way of knowing how confident they should be in the design choices that they make. This unknown certainty creates a substantial risk to using LCA results for marketing efforts and limits one of the major potential benefits of the analysis.

LCA work requires a solid understanding of the environmental issues of concern and the ability to construct process models and gather pertinent data. The special skills and significant time required preclude the average design engineer from performing the analysis. This is unfortunate because it hinders the desired learning among the designers. Without this learning, designers are unlikely to accept environmental concerns as relevant to their work, a necessary condition for true product environmental performance to occur.

Lastly, in order to perform a full LCA the product design must be complete. One of the primary objectives of DfE is to address environmental concerns earlier in the design process - before all the critical design choices are made. The LCA is essentially a post-mortem evaluation of the product that has little impact on the current product's design. However, the LCA does provide information that would be useful for the development of the next generation of product. Although we have not observed any such uses of LCA results, United Technologies Automotive is beginning to work in this direction.[45]

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[45] Rimawi, Ennis, "The Development and Introduction of Emerging Environmental Design Tools to Provide a Differentiating Capability for an Automotive Supplier," MIT Master's Thesis, June 1996.

In general, UTC and Motorola should be commended for their pioneering work with LCAs. The problems that we identify here are not unique to their situations but are inherent in the LCA methodology and its current implementations. This work will remain largely academic, however, until an attempt is made to tie the data more closely to the product design process.

4.5 DfE Management Systems

4.5.1 Benefits

The development and use of DfE Management Systems by companies is a recognition that environmental concerns are best addressed when they are incorporated into the existing management systems. There are several benefits to adopting such a system:

- minimizes the disruption to existing systems (e.g. product development system)
- allows consideration of the needs of different participants within the development process
- makes it possible to create a consistent system across an industry/company
- makes it possible to integrate various design/development tools

One of the fundamental goals of developing a DfE system is to incorporate it into the existing product development process. The more closely the systems are integrated, the lower the resistance to use by designers and engineers. The Tiered

Methodology developed at Motorola uses the product development process as its foundation and incorporates environmental needs via a series of stand alone tools During a pilot class for the Tier 1 Tool, the feedback from several engineers was positive and focused on the tool's ease of use and fit as part of the cross functional team's design process[46]. In addition, many of the class participants were surprised to learn the many environmental issues that they could influence and address during the design process. The tool appeared to help the engineers recognize environmental issues and prompt them to consider possible solutions.

The participation of individual members will vary during the course of development depending on the individual's knowledge and the specific phase of development. Therefore, it is important that the DfE management systems developed address the many disciplines involved during the various stages of a project. For example, the Tiered Methodology divides the product development process into three phases and attempts to address the needs of each phase. This is valuable as each phase involves different amounts of information about the design and different skills.

An important benefit of developing a management system is the consistency it can provide across a company or industry. This consistency makes it possible to develop tools and databases that are useful to many groups and leverages the knowledge within different divisions or companies. For example, the US electronics

[46] Based on Tier 1 pilot course feedback within two sectors of Motorola.

industry has become increasingly aware of the need for a strategic, coordinated approach. This has resulted in the development of the "Electronic Industry Environmental Roadmap". "This roadmap will help the electronics industry maintain a competitive edge in the international market and keep up with foreign competitors who benefit from well-established government/industry partnerships for addressing environmental issues."[47]

The DFESH management system under development at Motorola is another excellent example of industry cooperation. SEMATECH (a partnership of semi-conductor companies) is working with Motorola to develop the system. The development of this type of joint effort also provides a large cost savings for a company. Cooperatively developed systems also avoid (or at least distribute) much of the public scrutiny that internally developed systems would attract.

4.5.2 Areas of Concern

Although the DfE management systems are still largely under development, several problems are already apparent. Some of our concerns include:

- information transfer is limited across development stages
- management system is not easily accepted across companies

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[47] Microelectronics and Computer Technology Corporation (MCC), *"Electronics Industry Environmental Roadmap"*, p. 5, Austin, TX. 1994.

- systems are focused on a limited number of life cycle stages
- lack of continuos improvement methodology

Single stage tool development projects limit the flow of information across product development stages. For example, the Tiered Methodology does not currently share information across development stages, instead it focuses on developing a series of independent tools. It is important that the tools under development are linked or tied to a common database so that all design team members have access to the same amount of information. This information transfer can improve the decision-making process of the team with regard to environmental needs.

The divisions need to work together and learn from the other's approaches. If a DfE system is developed for the company as a whole, it will save money on duplicate efforts and provide a united effort towards meeting environmental concerns of customers. The system can be a framework and then specific applications can be developed for division specific needs. For example, the Tiered Methodology is beginning to be accepted company wide, but there needs to be more division involvement for this to occur. Currently most of the Tiered Methodology work is done by a corporate group with several divisions participating at various levels of involvement.

Another concern about the DfE management systems is that they tend to focus on a particular life cycle stage or impact area. For example, the SEMATECH system is focused entirely on the impact of manufacturing processes. The lack of focus on product use and disposal was a conscious choice as SEMATECH believes that manufacturing is where the majority of environmental impact occurs.[48] This may be true, however, ignoring a particular impact area could have consequences in the future as companies learn more about their product's impact or external factors shift.

One particular area that appears to be lacking from the management systems we observed is a systematic method for improving the DfE system on a continuous basis. An important part of a newly developed management system is the opportunity for reflection and enhancement. This allows the process or system to be updated and improved continuously. This is especially critical because the DfE systems are in the early stages of development.

4.6 Summary

In examining the characteristics, benefits and drawbacks of the DfE projects, we identified several recurring themes. Concepts such as data transparency and uncertainty tracking are import regardless of the application. We also found that some broad, high level themes are missing from the individual efforts. These

[48] Based on interviews with Motorola SEMATECH developers

system level attributes are critical for the development of an integrated, broad based, and useful DfE approach.

While this list is certainly not complete, it includes important characteristics that must be incorporated into any DfE system.

- Allows data to be shared across the company (economies of scale)
- Applied consistently and uniformly across the company
- Forces consideration of all stages of the life cycle
- Provides data transparency[49] and uncertainty tracking
- Provides the information necessary for various levels of decision-making
- Allows for continuous improvement and feedback

In the following chapter, we describe the characteristics in greater detail and outline our vision of a DfE process. In addition, we include a practical example of a design project to demonstrate how the system might work.

[49] Data Transparency is the ability to explore the data that underlies the results presented. For example, a product managers discovers that a particular assembly has a poor score for emission of ozone depleting chemicals. Data transparency would allow the manager to "drill down" into the data and discover the part and then the process responsible for the score.

5. The Product Oriented DfE System

5.1 Introduction

The purpose of this chapter is to construct a DfE system based on the characteristics listed at the end of Chapter 4. The chapter begins with an explanation of DfE as a process. This system level approach is justified by drawing on accepted TQM ideas. Next, a basic product development methodology is reviewed as a foundation for any DfE system. Finally, each major step in the DfE system is explained both in theoretical terms and using an illustrative example constructed from our experiences at the sponsoring companies.

5.2 DfE is a Process

Design for Environment (DfE) is commonly defined as a design *process* in which environmental attributes are treated as design objectives[50]. Because the DfE process is immature, it benefits from a TQM approach of continuous improvement.

> *"According to TQM because every product or service is the outcome of a process, the effective way to improve quality is to improve the process used to build the product*[51]*."*

Thus, we suggest that focusing on the process of DfE is the best approach to take in formulating DfE strategies. Product development is a crucial competitive activity for many companies and cannot be disrupted. By focusing on the process of DfE within the context of product development, it is possible to improve both systems together.

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[50] Office of Technology Assessment; Green Products by Design, Page 7

[51] Shiba, Graham, Walden; A New American TQM, Page 45

The methodology described below begins by conceding that there are still many unknowns, controversies and value judgments inherent in product environmental performance measurement. Rather than attempting to gloss over, or rationalize these difficulties, we include accounting mechanisms for measuring and tracking the uncertainty and incompleteness of the information. Our system utilizes this information for management decision making. The result is a DfE methodology that will improve together with the environmental performance of the products that it is applied to.

5.3 The Product Oriented DfE System

5.3.1 A Review of Product Development

We begin with a short review of the product development process. Product development methodologies vary from company to company and group to group, however, we believe that the fundamentals are largely the same. The differences stem mainly from varying levels of formality and control as well as development times. The model we present here is drawn primarily from the work of Ulrich and Eppinger.

5.3.1.1 Concept Development and System Level Design

Early in the product development process, the project management team meets to establish the fundamental features and goals of the product. Customer involvement will either be direct (common in the defense industry), or via marketing surveys and focus groups (common in the consumer products industry). The team evaluates market conditions, competitive products, customer and regulatory requirements and then attempts to establish goals that best address these often conflicting interests.

The goals establish what basic needs the product will meet. Example product goals might be; the car will cost less than $15,000, or the phone will weigh 10% less than the best competitor. It should be noted that often times the goals are established in terms of relative performance to either competitive or past generation products.

This is important because it highlights the fact that more often than not, there is substantial information available about the product before the design has even begun.

5.3.1.2 Establishing Product Specifications

Once the customer requirements have been identified and the product goals have been set, the design team must translate the goals into engineering and performance specifications. The difference between goals and specifications is that goals are often recorded in the "language of the customer,[52]" while specifications must be written in terms of quantities that can be precisely measured. Regardless of the method used, the result of this step is a list (sometimes referred to as the contract book) of specifications that the product will meet when the design is completed. The job remains for the designers to determine the best way of accomplishing the objectives.

5.3.1.3 Detail Design

During the detail design phase, the engineers are involved in evaluating tradeoffs:

1. Cost versus Quality
2. Durability versus Weight
3. Functionality versus Appearance

The environmental performance of the product will cause further tradeoffs to be made. Designers use computer aided design (CAD) and other tools to assist them in evaluating these tradeoffs. Typically, this process is highly iterative. The design is completed once, checked for compliance with all applicable specifications, and adjusted to correct deficiencies. Depending on the complexity of the design, this

[52] Ulrich and Eppinger, Product Design and Development, page 54

loop may repeat many times until an acceptable design is reached. The design tools serve several general purposes:

1. Evaluate the design's performance for particular metrics
2. Compare the performance of two or more designs
3. Store previous designs for reuse/modification
4. Provide "data transparency"
5. Allow for uncertainty and sensitivity analysis
6. Suggest changes that will improve performance

5.3.1.4 Testing and Iteration

During the testing phase, the product development team builds prototypes and evaluates the performance of the design. The first part of this reflection is examining the results of the development effort with respect to the goals and specifications that were set in Steps 1 and 2. The performance of the product is carefully evaluated along many metrics. Disappointing scores may result in design iterations or merely be recorded for the benefit of future design teams. Regardless, the information gathered forms a crucial platform for additional work.

5.3.1.5 Production Ramp Up

The last step in the product development process is the ramp up to full scale production. The manufacturing processes are refined, the workforce is trained and the product is released for sale. Capacity and volume increase as the production facility negotiates the learning curve. The quality and performance metrics of the final product are measured and small design adjustments are still possible.

The design team should also reflect upon the entire design process. Important issues or problems are recorded for the benefit of future teams. Some organizations (such as Carrier) reconvene the design team more than a year after product release to reflect on the design effort and any issues that have arisen via customer feedback. The goal of this reflection is to continuously improve the product development process as well as future generations of the product itself. In this way, the organization learns together with its employees.

5.4 The DfE System

The Product Oriented DfE System is a five step system that mirrors the product development methodology described above. The steps are as follows:

1. Set Product Environmental Goals
2. Set Engineering Specifications
3. Detailed Design
4. Evaluate Environmental Performance
5. Reflect and Improve the Process

The intent is to provide the information that is pertinent at each stage of the design effort without adversely impacting the performance of the team. In addition, we discuss the feedback that is necessary in each step for continuously improving the DfE system as a whole.

5.4.1 Step 1: Setting the Product Environmental Goals

5.4.1.1 Explanation:

The product's environmental improvement goals should be established by the product management team. Financial, manufacturing, marketing, regulatory, and other burdens are not ignored, but rather are crucial, explicit factors in setting the environmental improvement goals. The product management team is asked to consider the available environmental performance information along side of the traditional marketing and performance data when determining the appropriate set of improvement goals. The exact method used to set the environmental goals is not crucial. In fact, when possible they should be set using the same methods used in setting other product goals (price, performance, features, etc.).

Environmental goals can take at least two forms.

1. **Specific Goals:** A specific goal is usually based upon external constraints generated by regulatory or market forces. For example, in the aerospace industry, the use of cadmium has become an important marketing issue. The United States Air Force has specified that the engine for the new F-117 will not contain any cadmium. Pratt and Whitney therefore has been forced to impose a specific "no cadmium" goal on all of the design teams (internal and external) participating in the F-117 development. Another example comes from the electronics industry. The Montreal Protocol agreement and Title IV of the Clean Air Act[53] specified the elimination of CFC production worldwide by the year 2000. The electronics industry, a heavy user of CFC based cleaners, drew immediate attention from environmental groups. This market-based pressure caused the industry to move quickly in developing CFC free cleaning methods and setting "no CFC" goals for its products.

2. **General Goals:** A general goal is derived from information that is believed to represent the best available knowledge of the "true" impacts of the product. General goals specify improvement in a particular impact area across all of the life cycle stages. An example of a general goal is to reduce the power consumption of a cellular phone by 10%. The designers are given the freedom to decide in which life cycle stage(s) the improvement is most easily obtained. Returning to the aerospace industry, a general goal would be to reduce the human toxicological impacts of an engine design. Depending on many factors, the design team might decide to replace certain high volume plating processes thus reducing by 80% the release of several toxic species. Rather than focus on

[53] Amendments of 1990

eliminating the remaining 20%, the team may determine that it is more cost effective to rewrite the maintenance procedures so that less toxic waste is generated during the "use" life cycle stage.

The product management teams requires certain information when setting the environmental performance improvement goals. Access to impact assessments of previous generations or similar products is very useful. When viewing this information, the management team needs to view the overall product performance metrics and the impacts associated with the major systems (or components) of the product. This type of data helps guide the team by highlighting the major areas of concern and the areas where improvement is needed.

The management team also requires information on the feasibility and the likely financial impacts of improvements in certain areas. For guidance in this arena, the team may call on the environmental and process "experts."

5.4.1.2 An Example

An aerospace supplier has been given the contract to develop a replacement engine controller for a military jet engine. The controller will replace one originally designed by the company several years ago. The new design is being requested to add significant new functionality to the product.

The customer, the Department of Defense (DOD), has specified that the new design will be "cadmium and lead free." They have also requested that material accounting be conducted so that they will be able to categorize major subassemblies during disassembly and disposal. The DOD has drawn a great deal of scrutiny for its environmental performance and would like to improve the recyclability of its products.

The product design team decides to adopt the "cadmium free" and "lead free" goals explicitly. The team also agrees to provide a material product content list to the DOD that will allow them to easily identify the material composition of subassemblies and parts. While contemplating the recyclability issue, the team requests an "expert" opinion. The companies environmental product design champion is consulted.

The environmental expert presents an analysis done using the Eco-points system. The analysis compares the relative environmental impact caused by the engine controller during its "use" and its "disposal" life cycle stages. The results clearly demonstrate that the disposal stage has significantly less impact on the environment than the use stage. The expert points out that this result is even more relevant in the US where the population is generally more concerned with toxic emissions and atmospheric change than with landfill use and raw material consumption. Given this information, the design team elects to specify a goal of improving the energy use of the controller by 3% compared to its predecessor.

5.4.2 Step 2: Engineering Specifications

5.4.2.1 Explanation

Ulrich and Eppinger[54] suggest a method for establishing the target specifications by first preparing a list of the appropriate metrics and then determining the target values to be achieved. Regulatory and market factors are useful for selecting the metrics while the performance of competitive (and/or predecessor) products is crucial in selecting the appropriate values. It is possible that Ulrich and Eppinger's method can also be applied to setting environmental specifications, however, little work has been done in researching this area.

Selecting the appropriate metric requires input from the environmental "expert" on the team. The goal of "reducing the human toxicological impact by 10%," could be measured in any number of ways. The Eco-points metric for heavy metals attempts to quantify the impact to human health of heavy metals (such as lead and cadmium) released to the environment. Other metrics, such as the LD30/50, DOT classification, or carcinogenic characteristics also reflect, in different ways, the impact of toxic materials on humans. The appropriate metric(s) are chosen based on several factors:

1. Public's acceptance of the metric (including the legal system)
2. Availability of data used by the metric
3. Requirements of any applicable regulations
4. Requirements of any applicable eco-labels

[54] Ulrich and Eppinger, Chapter 4

Once the appropriate metrics have been selected, the life cycle stage(s) that are to be targeted must also be determined. If environmental specifications can be set without restricting the life cycle stage(s), it should be done. This leaves the designers with the most freedom and flexibility for identifying efficient solutions.

The assessment of which life cycle stages are the most significant requires an understanding of the different ways that the product can register with the metric. Senior level designers, environmental experts and engineers are the best team members for making this determination.

The senior engineers and environmental experts require specific information when selecting the metrics and specifications for the product. The environmental goals created in Step 1, of course, play an important role. Additionally, the environmental expert needs access to the life cycle models that are appropriate for the metrics of interest. For example, if the goal is to limit the release of greenhouse gases, the environmental expert needs to understand the emissions resulting from the manufacturing, use and disposal of the product. A lack of information about any one of theses stages could lead to a situation where the major impact source is ignored.

5.4.2.2 An Example

The engine control design team is selecting the environmental metrics upon which to base it latest design for the project. There are several possibilities under consideration based on the goals set by the customer and the product manager.

Cadmium and lead use are to be eliminated entirely from this product. Several metrics arise directly from this, *specific* goal.

1. Cadmium Product Content
2. Lead Product Content
3. Waterborne Cadmium Emissions
4. Waterborne Lead Emissions
5. Airborne Cadmium Emissions
6. Airborne Lead Emissions

In plain English, the product can not contain any cadmium or lead, or utilize any processes that emit wastes of these materials to either the air or water. These metrics are already present in the DfE system knowledge base therefore no further work is necessary. (Figure 5-1) The team, however, decides to add the additional specification of reducing the Human Toxicity Metric (Eco-Points definition) by 5% over the previous design. Cadmium and lead are only two of the many contributors to the human toxicity metric.

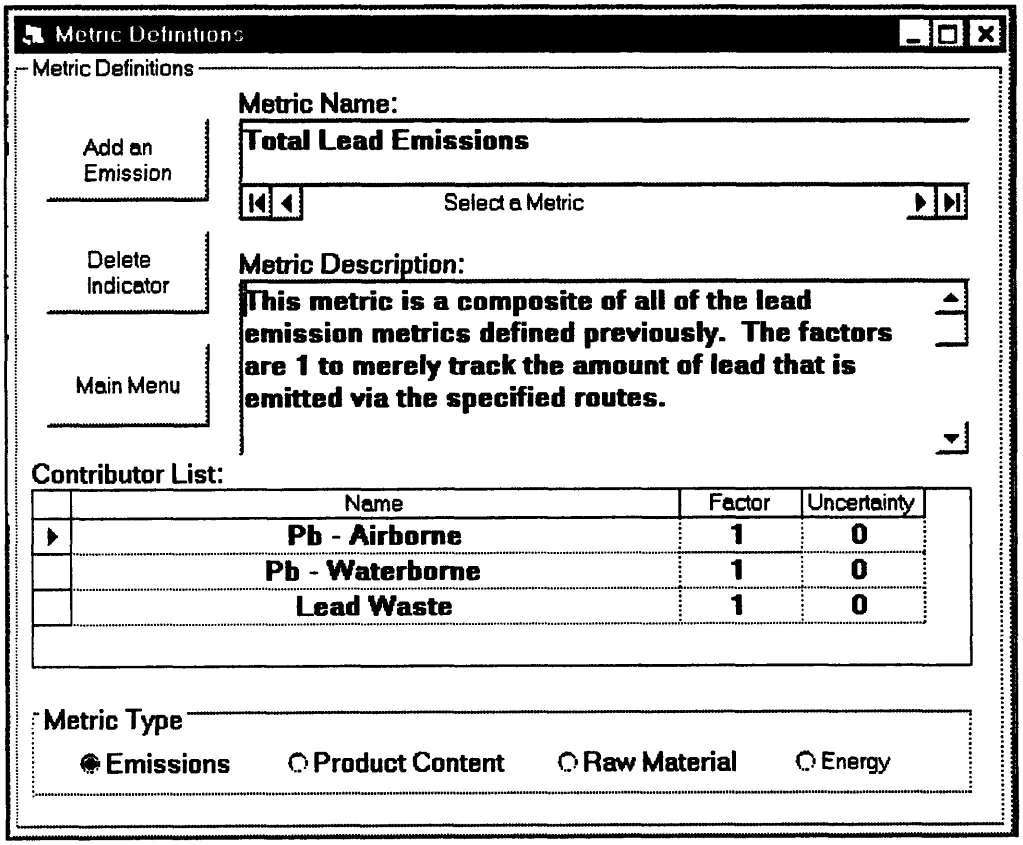

Figure 5.1: An Example Metric Definition

5.4.3 Step 3: Detailed Design

5.4.3.1 Explanation

During the detailed design phase, the majority of the environmental characteristics of the product are being determined. The designer is making decisions that will impact the environment for many years. Generally, when the design is complete, so too are decisions about manufacturing processes and materials. Even the impact of remote life cycle stages such as use and disposal are predominantly determined by the design details. For this reason, the importance of this step cannot be over emphasized.

Our DfE system depends on the detailed designer making decisions that will allow the environmental specifications and goals to be met. In order for this to occur, the designer needs a great deal of information upon which to base his or her decisions. Lack of information and the inability to present the available information at the crucial time are major obstacles to DfE practice. Overburdened designers need the data to be presented in such a manner that it is convenient and consistent (in appearance, etc.) with the tools they currently use. For this reason, a software package that is integrated with their existing design tools is the preferred solution.

Ideally, the designer could easily evaluate the performance of a part in terms of the appropriate metric. If the performance is not satisfactory, the designer then identifies the processes that are causing the poor results. Substitute processes or scenarios are chosen and the performance is reevaluated. Other metrics (environmental and other) are also reexamined to ensure that the change has not forced other parameters out of specification.

Designers should consider the "quality" of the data that they are evaluating when considering possible tradeoffs. We define data quality in terms of the two errors that are possible when defining a process:

1. Uncertainty
2. Incompleteness

The designer uses the uncertainty and completeness measures to justify decision making. For example, there has been much debate over the environmental impact of paper versus polystyrene (foam) beverage containers. During the last few years it has been suggested that paper cups are environmentally preferable to foam cups. However, as demonstrated by Hocking, a detailed analysis reveals that polystyrene cups should be given a more "even-handed" assessment in terms of its environmental impact relative to paper cups[55]. Ignoring the confounding issue of differing value judgments[56], a possible explanation for the discrepancy is uncertainty. Without information about the uncertainty associated with the numbers, it is impossible to determine if, in fact, the paper and polystyrene cups have statistically distinguishable environmental impacts. How then is one to justify the decision to use paper or polystyrene cups? We conclude that it is inappropriate to make design decisions without the type of "data quality" information that our system provides.

Information from the DfE knowledge base is crucial for the decisions that the designers are making in this step. The knowledge base contains the process models that are used to define the parts and assemblies. When the designers run an analysis of a particular part and metric, all the processes that make up the part are surveyed for contributors to the metric. The process uncertainty and the completeness scores are propagated through the calculations so that the final number accurately reflects data quality.

[55] Hocking, Martin B., "Paper Versus Polystyrene: A Complex Choice", Science Vol. 251. 1 February 1991.

[56] Value judgments refers to the process of comparing different environmental impact areas. In the debate over diapers, weighing the impact of filling the landfill with plastic disposables, versus depleting the water and energy that are used while washing cloth diapers. In California, where water is scarce, the problem of overfilling the landfills may not seem as important. These value judgments are highly dependent on the society for which the evaluation is conducted. Our system chooses to focus instead on single metric accounting and analysis allowing each company to impose the set of values that it feels are appropriate for the society in which it operates.

5.4.3.2 An Example

A designer for the engine controller project, is assigned the task of designing the electromagnetic shields for the circuit boards within the engine controller. She has already designed a steel EMI that was used on a previous project. However, she recently learned that several design teams have had success with less expensive, plastic shields. She is skeptical but her manager insists that she try this new shield. She is also curious as to how the new shield will compare with the old shield in terms of the environmental specifications listed in the contract book:

1. recyclable material content
2. heavy metal emissions (and lead and cadmium free)
3. ozone depleting chemical emissions

5.4.3.3 Use of DfE System

The designer needs to follow several steps using the DfE System in order to determine which shield is a better choice from an environmental perspective. The steps are outlined as follows:

1. define the new part - plastic shield
2. compare the two shields
3. determine if one shield is *significantly* better than the other
4. examine the possibilities for improvement

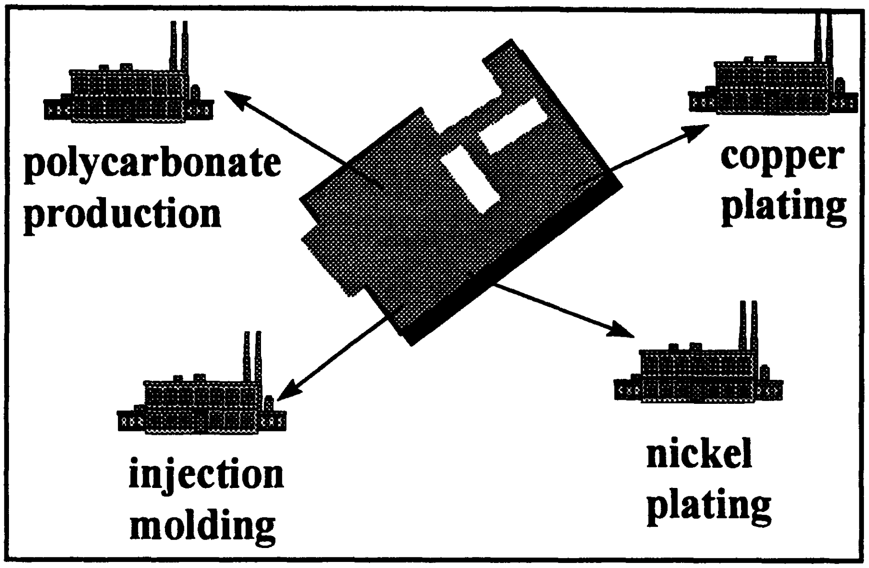

Figure 5.2: A Typical Plastic EMI Shield

The first step is to define a plastic EMI shield within the DfE system based on the available information. The major processes that define the plastic shield are shown in Figure 5-2. A screen, similar to the one shown in Figure 5-3, prompts the designer to select the processes and enter quantities for the amount the process contributes per unit of part produced. In other words, for the injection molding process a value of 1.0 is interpreted as for each unit of plastic shield produced one unit of the injection molding process is used.

For copper plating, each unit of plastic shield produced results in only 0.025 units of copper plating process being used. This factor is used to determine the amount of emissions and material content that can be attributed to one unit of plastic shield production.

When entering a quantity for each process, the designer also records an uncertainty amount. This value is used to statistically represent the spread associated with the number. The designer is asked to specify the range over which they are confident[57] that the actual value lies. Obviously, the lower the uncertainty, the smaller the range in which we are likely to find the actual value. Standard propagation of error techniques are used to compile the uncertainty associated with the entire part or assembly. This overall uncertainty value aids the designer by giving them confidence that the numbers they are using to make decisions are significant. For example, a designer is confident that the actual value for a certain process is between 0.9 and 1.1 grams. The amount is entered as 1.0 and the uncertainty as 0.1 grams.

[57] The intent here is to treat the interval specified by the designer as a 95% confidence interval for the purposes of error calculations. Other confidence intervals can easily be substituted.

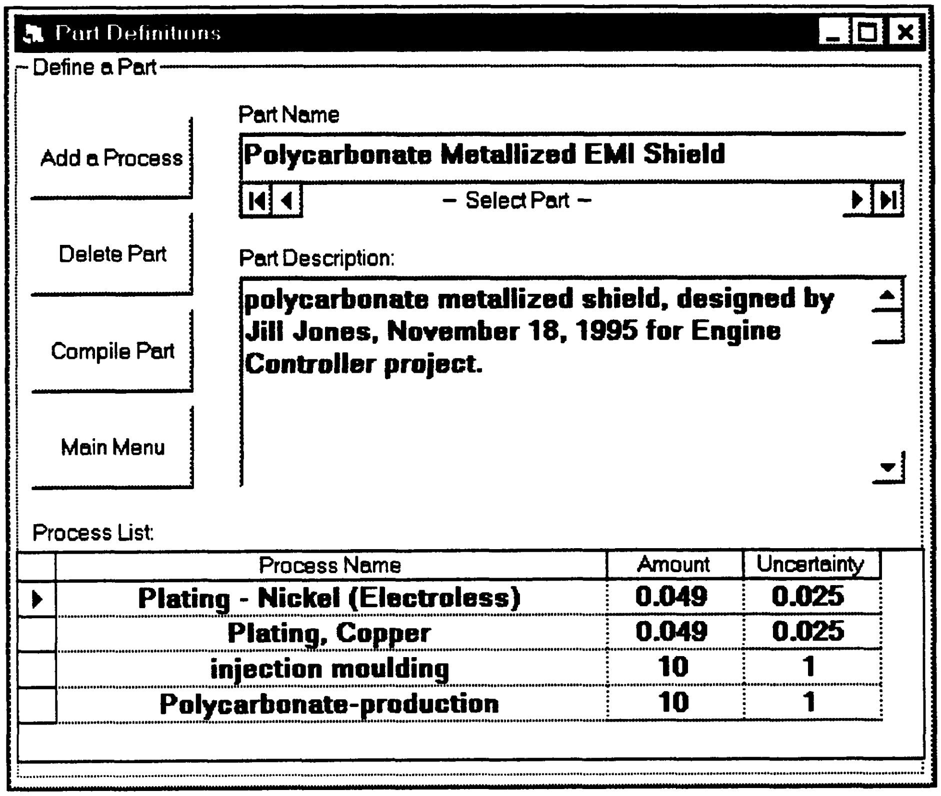

Figure 5.3: EMI Shield Definition Screen

Once the part is entered, the designer's next step is to compare the plastic shield to the cold rolled steel shield to find out if one is environmentally preferred. The parts are compared based on the three metrics outlined in the contract book. Then a report is generated that provides an analysis report of the parts. A summary of the report is shown in Figure 5-4. An interesting point to note in the report is that the steel shield did worse in the heavy metal metric than the plastic shield.

After reviewing this information, the designer wants to know why the steel shield performed worse and what can be done to improve its environmental score. She generates a detailed report about the steel shield viewing it through the lens of the heavy metal metric. The report (Figure 5-5) identifies the nickel-plating process as the major heavy metal contributor.

The designer then uses the similar process feature (Figure 5-6) to quickly check the database for any possible substitutions for the nickel plating process. The substitutions listed may be other nickel plating processes, or perhaps even the identical process but from "greener" suppliers. The designer now has sufficient information to make an informed decision as to which shield she prefers to use for the engine controller.

Metric #1 -- Ozone Depleting Chemicals

---Assembly #1 – Nickel Plated CRS Shield
------Score: 0.00E+00
------Uncertainty: 0.00E+00
---Assembly #2 – Plastic Shield
------Score: 0.00E+00
------Uncertainty: 0.00E+00

Metric #2 -- Heavy metals

---Assembly #1 – Nickel Plated CRS Shield
------Score: 1.21E+00
------Uncertainty: 1.35E+00
---Assembly #2 – Plastic Shield
------Score: 2.47E-02
------Uncertainty: 2.75E-02

Metric #3 – Recyclable Content

---Assembly #1 – Nickel Plated CRS Shield
------Score: 1.37E+01
------Uncertainty: 1.35E+00
---Assembly #2 – Plastic Shield
------Score: 5.15E-01
------Uncertainty: 5.06E-02

---Data Completeness Analysis---

Assembly #1 has an average completeness score of 3.
Assembly #2 has an average completeness score of 4.

Figure 5.4: Results of the Comparison

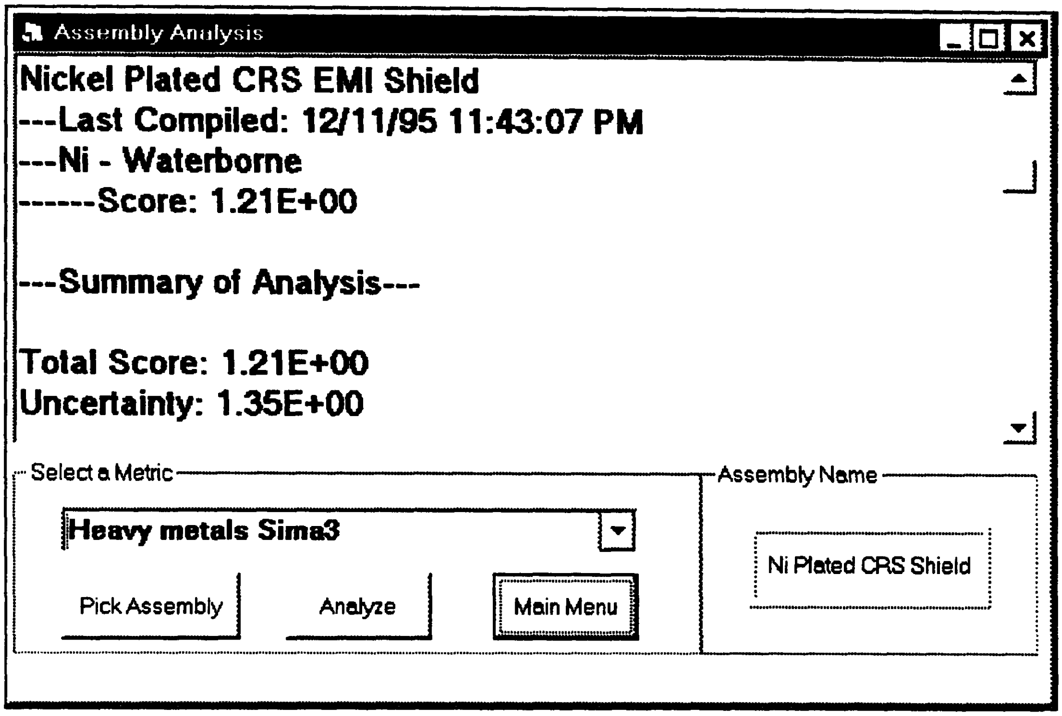

Figure 5.5: Nickel Plating is the Major Heavy Metal Contributor

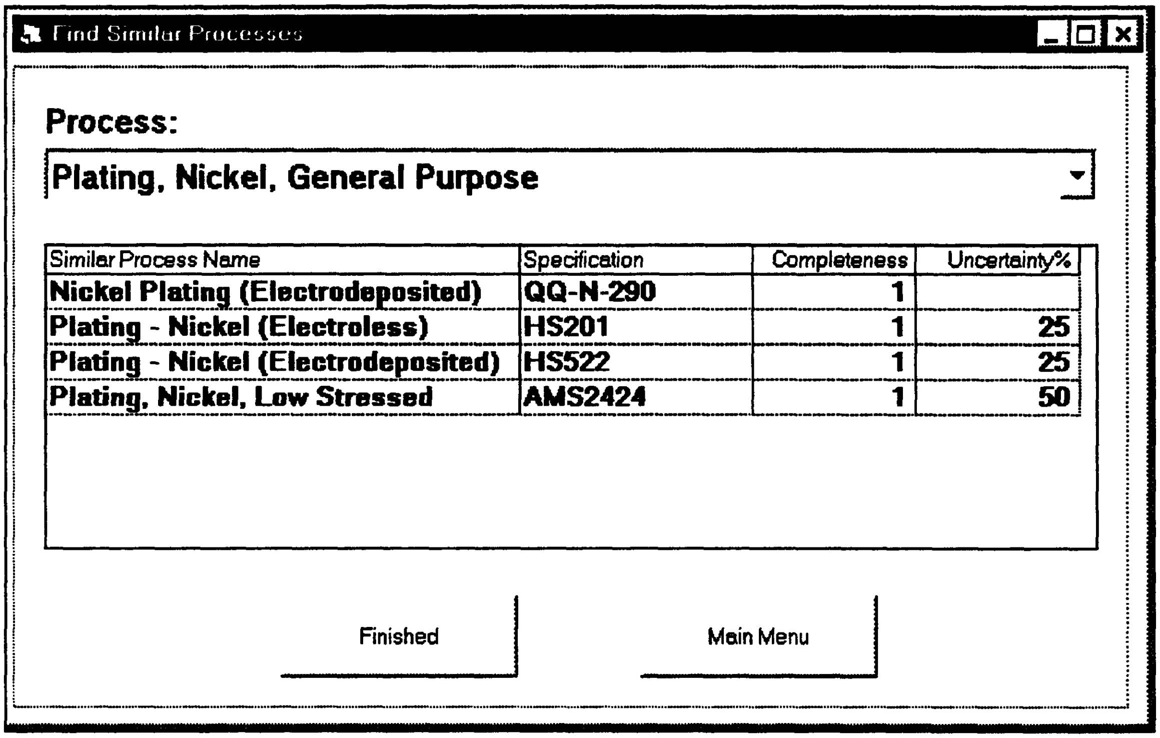

Figure 5.6: The Database Suggests Process Substitutes

5.4.4 Step 4: Evaluate Environmental Performance

5.4.4.1 Explanation

This stage is the one most often associated with DfE. The problem of assessing the environmental impact of a product has received a great deal of attention and research effort[58]. This should not be a surprise. Making environmental improvements to products requires that one has some knowledge about what impact they currently inflict. However, because life cycle inventory assessments

[58] U.S. EPA, Life Cycle Design Guidance Manual: Environmental Requirements and Products System

have proven so difficult,[59] and the impact assessments so controversial,[60] there has been a reluctance to utilize the information for decision making.[61]

We feel that these concerns, while valid, should not preclude the decision making and environmental improvement processes. A system that accounts for data quality allows decision making to occur at the appropriate comfort level.

5.4.4.2 An Example

Suppose the EMI shield designer is again comparing the two shields, this time she is examining the Ozone Depleting Chemical Emissions Metric (Figure 5-7). At first glance, she is pleased to note that neither design emits ozone depleting chemicals; both scores are zero. However, the average completeness score of the plastic shield is only two, while the CRS shield has a score of seven. The designer decides that the difference is large enough that the plastic shield's good ozone score should be discounted.

Thus, the decisions as to environmental improvement are made not just using the "best" information available, but also with quantitative indications of how "good" that information is. The decision maker now uses his or her judgment to justify product changes.

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[59] SETAC, "A Technical Framework for Life Cycle Assessment"

[60] Curran, Mary Ann, "Broad-Based Environmental Life Cycle Assessment", Environmental Science Technology, Volume 27, No. 3, 1993, p. 434.

[61] Arnold, Frank, "Life Cycle Doesn't Work", The Environmental Forum, September/October 1993, p. 21

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---Comparison Results---

Metric #1 – Ozone Depleting Emissions

---Assembly #1 -- Plastic Shield
------Score:       0.00E+00
------Uncertainty: 0.00E+00
---Assembly #2 – Nickel Plated CRS Shield
------Score:       0.00E+00
------Uncertainty: 0.00E+00


---Data Completeness Analysis---

Assembly #1 has an average completeness score of 2.
Assembly #2 has an average completeness score of 7.

--- Analysis Complete ---
```

Figure 5.7: Data Completeness

Step 4 is largely about improving the *quantitative* data in the knowledge base. The environmental "expert" is focused on capturing as completely as possible the process models that are used in defining the parts and assemblies. Early in the development of the DfE system, this task is extremely challenging due to the historical lack of data. Over time, however, the number of processes that have been modeled will grow and the emphasis will shift from capturing new processes to updating old ones. (See section 5-3 on management decision making)

Another important activity that occurs during this step is product certification. Generally, there are a set of strict requirements that must be met before an "eco-label" can be affixed to the product. A part of the certification process may involve calculating certain, precisely defined metrics which may or may not already be included in the knowledge base. Our system allows an individual to easily add new metric definitions (Figure 5-1) to the database, without massive changes to the existing data. This attribute is doubly important given the dynamic nature of environmental standards and metrics.

5.4.5 Step 5: Reflect and Improve the Process

5.4.5.1 Explanation:

While Step 4 reflects and measures the output of the DfE cycle, this step focuses on improving the DfE process itself. The design team should document their thoughts and ideas about how the process could be improved. This "improvement plan" serves as guidance for the environmental expert and for future design teams. The process of DfE thus evolves over time so that it remains applicable as markets, processes and tools change.

Improving the system requires that the management team supply feedback. This feedback should cover at least a minimum set of issues.

1. **Data Completeness:** The team should recount on the sufficiency of the data for decision making. Early attempts will mostly likely report this to be a problem because data collection efforts are slow. These reports, however, will be invaluable for focusing collection energy on the type of information that is necessary for decision making.

2. **Data Uncertainty:** The uncertainty associated with the data that is available will impact the willingness of the management team to specify improvement goals or design changes. The appropriate uncertainty level is best determined by the decision makers themselves through their feedback.

3. **Data Format:** The manner or format in which the information is presented to the management team is an important component of its usefulness. The team should suggest changes to better integrate the

environmental information with the tools or methodologies used in each step. The level of detail is a crucial variable in this area.

4. **Information on Alternatives:** Goal setting is difficult without information about the feasibility of improvement and alternatives. A lack of this type of data could leave the team unable to specify appropriate and realistic goals.

5. **Financial Information:** Data on the potential cost or savings that will result from reaching environmental goals will be particularly difficult to gather due to the large uncertainties and approximations required. The team should reflect on what improvements are needed in this area.

The environmental "expert" relies on information from the designers to determine which processes are in need of improved models. They may also determine that R&D is needed to find substitutes for certain, important processes. This feedback is necessary for the long term improvement of the DfE system because it helps management assign priorities and justify funding.

The information that is transferred during Step 5 takes the form of an improvement plan generated by the design team. The company should develop a report template to aid the team in structuring their reflection. A sample template is included as Figure 5-8.

Figure 5.8: Improvement Plan Template

Step 1: Set the product environmental goals

Ratings/Comments:

Quality of Available Information, Quantity of Available Information, Goals Setting Methodology, Biggest Obstacles to Goals Setting, Integration with Design Process

Specific Suggestions for Improvement:

Step 2: Set the product's environmental specifications

Ratings/Comments:

Quality of Available Information, Quantity of Available Information, Specification Setting Methodology, Biggest Obstacles to Setting Specification, Integration with Design Process

Specific Suggestions for Improvement:

Step 3: Detail Design

Ratings:

Quality of Available Information, Quantity of Available Information, Biggest Obstacles to Detail Design, Integration with Design Process and Tools

Specific Suggestions for Improvement:

Step 4: Evaluate Environmental Performance

Ratings:

Evaluation Methodology/Tool, Biggest Obstacles to Evaluation, Amount of Resources Used in Evaluation, Integration with Design Process

Specific Suggestions for Improvement:

Step 5: Reflect and Improve the Process

Ratings/Comments:

Quality of Reflection, Goals Setting Methodology, Biggest Obstacles to Reflection and Improvement, Integration with Design Process,

Specific Suggestions for Improvement:

5.5 Management Decision Making

In addition to the design group's activities, the DfE system supplies information that is useful for management. Specifically, the knowledge base allows company research funds to be allocated in an efficient way. Clearly identifying the weaknesses of the data allows the decision maker to understand where research is needed and to estimate what its impact will be on the quality of the information available to the design teams.

The system's feedback mechanism also aids the policy maker in prioritizing traditional research projects. Designer's comments on the feasibility of replacing cadmium plating, for example, make it easier to justify R&D projects targeting the development of replacement materials. Importantly, the feedback also helps identify the specific applications where substitutes are most needed. This "focusing" of R&D expenditures is an important benefit of the DfE system.

5.5.1 An Example

A materials engineer, has recently been asked by management to make some recommendations on where the group should focus their research efforts in terms of gathering data on processes. The processes within the system are all at different levels of detail depending on information available at the time they were entered. There are many processes that can be studied, but time and resources are limited. In the past, the group made educated guesses as to the processes that are most important to study but this has been a point of much debate.

5.5.2 Use of DfE System

In order to make some recommendations, the materials engineer can use the DfE System to quickly generate a report that provides information about the quality of the database. The report is generated based on the following criteria (Figure 5-9):

- the date that the process was last updated
- the average uncertainty of the process data
- the process completeness score
- the number of parts that use the process

Each time a process is entered or updated within the database the date and completeness scores are updated. The date provides a measure of how often the database is updated and monitored. The completeness score is a measure of the quality of information provided about the process. The average uncertainty score is another way to determine the quality of information within the database. Finally, the last criteria provides an indication how often a process is actually used by designers to design parts. Based on the values entered for each of these criteria a list of processes is generated, providing the needed information for determining where to focus research efforts.

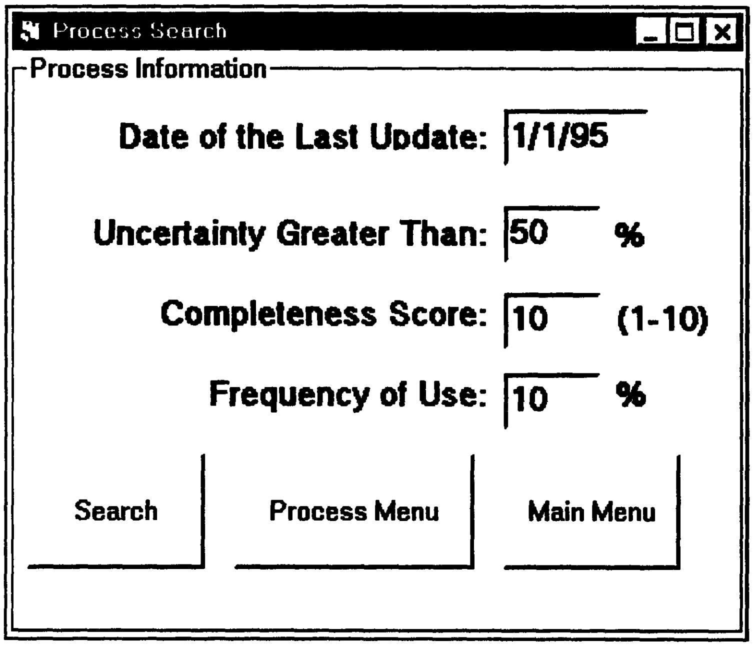

Figure 5.9: Selecting the Search Criteria

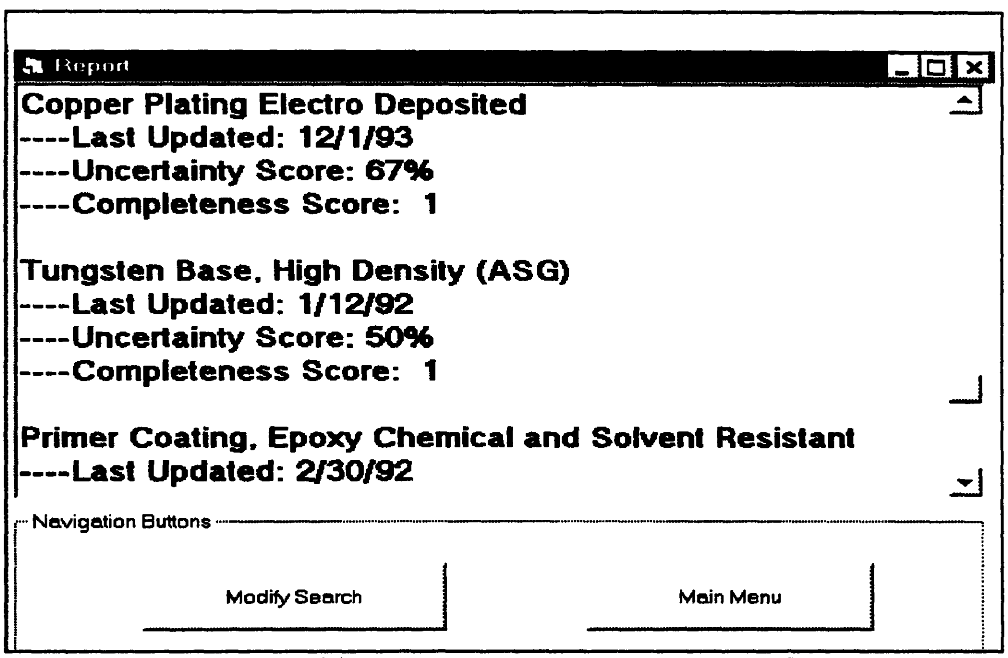

Figure 5.10: A Typical Report on Process Model Quality

In this case, the engineer has specified that processes that have not been updated in the last two months, have completeness scores less than 5 and uncertainty scores of greater than 20% are where efforts should be focused. A list of processes that meet these criteria give him the necessary information to make a recommendation for future research efforts. A sample of the report is provided in Figure 5-10.

5.6 Summary

The DfE system that we propose has been outlined above. We believe that it addresses the concerns identified in Chapter 4 and listed again below. The examples described here demonstrate a practical application of the system while identifying the difficulties that still remain. In the last chapter, we propose some general recommendations for companies that are considering DfE implementation.

Major Features of DfE System

- Allows data to be shared across the company (economies of scale)
- Applied consistently and uniformly across the company
- Forces consideration of all stages of the life cycle
- Provides data transparency[62]
- Provides the information necessary for various levels of decision-making
- Allows for continuous improvement and feedback of the system itself

[62] Data Transparency is the ability to explore the data that underlies the results presented. For example, a product managers discovers that a particular assembly has a poor score for emission of ozone depleting chemicals. Data transparency would allow the manager to "drill down" into the data and discover the part and then the process responsible for the score.

6. Implementation & Recommendations

6.1 Introduction:

In the previous four chapters, we examined the state of the art of DfE from a variety of perspectives. We spoke in general terms of the typical approaches being taken and gave very specific examples taken from our experience at two diversified manufacturing companies. Next, we described our idea of a DfE system complete with illustrative examples. In the following sections, we conclude our work by addressing the implementation plan and by making some general recommendations for companies, such as Motorola and UTC, that are considering the DfE question.

6.2 DfE System Implementation:

Implementing the DfE system we outlined will not be a simple task. Extensive research remains to be done and the development will require the coordinated effort of multiple sectors and various functional expertise. Full scale implementation will also be expensive. The resources required to model all of the necessary processes and to develop all the tools, training materials, and databases have not even been estimated.

All is not lost, however, because the pull for a DfE system remains distant. A cautious and deliberate development is the best approach so long as the company remains cognizant of changes in the external factors. The effort should begin with further planning and an attempt to garner buy-in from upper level management. Issues such as pending ISO standards and product stewardship regulations can be pointed to along side of less ominous factors such as eco-labeling and community activism. Once buy-in (and initial funding) is achieved, work can begin on the implementation plan outlined below. It should be noted that we are not proposing that all of these projects be undertaken simultaneously, rather that each needs to be completed for full scale implementation to be a success. We recommend that a natural succession be followed at the pace funding will allow. An early pilot, in a single sector/company, should be the most efficient approach since it maximizes learning while conserving the scarce resources of money and time.

6.3 The Major Implementation Projects

6.3.1 Education

The purpose of the education project is to prepare the extensive training program that must be established before the DfE system is implemented. Training should cover background and motivation issues with technical issues being addressed in more advanced, specialized classes. The training is also a crucial step in gaining the "buy-in' at all levels within the organization.

6.3.2 Monitor External Factors

This project is necessary because of the rapidly shifting nature of the environment facing the DfE implementation teams. Choosing the appropriate metrics, understanding the customer's needs, and keeping current with the ever changing regulatory atmosphere are the primary objectives of this project. It should be one of the earliest to receive attention and funding.

6.3.3 Software Tool Development

Developing an integrated set of software tools is a crucial piece of the DfE implementation. Tools must integrate not only across product development stages, but also with the design or decision making tools currently in use. This is important if environmental variables are ever to be considered concurrently with other design constraints.

6.3.4 Modify Product Development Process

This team should examine the current product development practices and procedures and determine an efficient way to include the environmental concerns. This effort should be conducted by experienced designers and managers who are sensitive to the demands of a competitive development endeavor.

6.3.5 Data Collection

Collecting the data necessary to fuel the DfE system is a daunting task. The work should begin by taking advantage of relevant public or commercial databases. Such sources are especially useful for common, externally controlled processes such as electric power generation or garbage incineration. The team must also develop its own models for commonly used, in house manufacturing processes. An important piece of this work will be measuring or estimating the uncertainty and completeness of the models. As discussed previously, these numbers are crucial for decision making. Currently, it is still difficult to quantify the effort needed to collect this type of data.

The figure below summarizes the implementation plan and its major projects.

Figure 6.1: Plans for DfE Implementation

Project	Education
Team Members	Representatives from Corporate Training and EH&S, Design, Engineering and Product Management
Project Phases	• Develop and Deliver Introductory DfE Course • Develop Function Specific Courses Together with Tool Development Teams • Periodically Update Basic Courses and Develop Refresher Courses
Project	Monitor External Factors
Team Members	Corporate EH&S, Environmental Technology Expert, Marketing
Project Phases	• Initial Survey of External Factors such as: Regulatory and Standards Organizations Requirements, External Data Sources, Customer Requirements and Interest Level • Deliver Survey Report to Tool Development and Data Collection Teams • Perform Periodic Compliance Reviews of DfE Implementation
Project	Software Tool Development
Team Members	Engineering and Design, Management, Software Engineer or MIS Expert
Project Phases	• Agree on Database Structure and Interface Standards • Survey Functional Groups for Tool Requirements and Integration with Existing Tools • Develop Beta Version Tools and Receive Feedback • Distribute Tools and Training
Project	Product Development Process
Team Members	Product Management, Functional Groups Representatives, Corporate Engineering or Design, DfE Expert
Project Phases	• Review Product Development Process Standards Company Wide • Update Product Development Standards to Include DfE
Project	Data Collection
Team Members	Materials Engineers, Design Engineers, Environmental Engineers, Manufacturing Engineers
Project Phases	• Internal Review of Major Processes • Review and Gather Data from Commercial Databases • Develop Additional Process Models as Needed • Review and Improve Database Quality

6.4 Summary

We would be remiss in our analysis if we did not acknowledge some of the issues that remain unresolved. Time and resource constraints aside, these items would add significantly to the depth of our work. We leave them instead for others.

1. **Cost/Benefit Analysis** - The costs associated with a full scale deployment, although uncertain, will be large. What financial benefits (if any) can the companies expect in return? Traditionally this is how large projects are evaluated. Environmental issues are different, but a cost/benefit analysis would be very useful in determining the pace at which implementation is driven.

2. **Scope** - In the days of outsourcing and concentrating on your "core competencies" much of the environmental impact of a product is controlled by companies other than the one whose name appears on the label. Who is responsible for these impacts? Should an OEM concern itself with the environmental responsibility of its supply chain? If so, then who pays? These are but a few of the questions that remain in this area. We would suggest that cooperation and information sharing are key, but admit to little research behind our counsel.

3. **Standardization** - Developing a DfE system in house is a risky endeavor. Regardless of the intent, such an effort will no doubt be met with skepticism from environmental groups. This is an important fact because one of the proposed benefits of a DfE system is the increasing "greenness" of customers in their purchasing decisions. Although no DfE system will ever be universally accepted, an internally developed one greatly increases the chance that environmental claims of the marketing department will be challenged. These liability concerns may preclude such attempts and destroy a potentially powerful competitive advantage. Work remains in finding a solution to this problem that is flexible to accommodate the differing design approaches across an industry.

This thesis represents an early attempt to address a very complicated and difficult problem. We do not profess to have answered or even identified every issue that will arise as DfE works its way into the design studios of major manufacturing firms. We do however, believe that the features we included in our DfE approach will be critical ones in any successful, large scale implementation.

In closing, we believe that the two companies we studied should be commended for their work in DfE. Although their approach remains slow and experimental, it represents leading edge development. In today's dynamic environment, a cautious approach is understandable but the expertise and experience that they are cultivating will prove valuable in the not so distant future.

7. Bibliography

"Guide To Environmental Management Principles Systems and Supporting Techniques - ISO 14XXX", *Working Draft*, ISO/TC207/SC1/WG2, July 13, 1994.

Allenby, B.R., Richards, D.J., Frosch, R.A., The Greening of Industrial Ecosystems. National Academy Press, 1994.

Bushan, A.K., Mackenzie, J.C., "Environmental Leadership *Plus* Quality Management *Equals* Continuous Improvement", Environmental TQM (Second edition), McGraw Hill, 1994.

Cook, Kelly and Fiksel, Joseph, "Design for Environment Survey Results", Decision Focus Incorporated., Mountain View, CA. August 1995.

Dillon, Patricia, "*Special Report: Environment* - Savageability by design", *IEEE Spectrum*, August 1994.

Ehrenfeld, John R., "Industrial Ecology: A Strategic Framework for Product Policy and Other Sustainable Practices", *Prepared for The Second International Conference and Workshop on Product Oriented Policy,* Stockholm, September 1994.

Gatenby, David A. and Foo, George, "Design for X (DfX): Key to Competitive, Profitable Products", *AT&T Technical Journal*, May/June 1990.

Gockel, Bruce C., Watkins, Randall D., Kleban, Stephen D., "Eco-SyS™- Supporting Green Design Through an Extensible Life Cycle Analysis Approach", SAND 95-1154C, Sandia National Laboratories, Albuquerque, NM, June, 1995.

Hoffman, Bill, "A Tiered Approach to Design for Environment", *Proceedings of IEE Conference: Clean Electronic Products and Technology,* Edinburgh, Scotland, October 1995.

Hunter, Rod, "European Electrical and Electronic Product Take-Back Regulation", The Bureau of National Affairs, Washington DC, June 14, 1995.

Institute of Electrical and Electronic Engineers. *Conference Record of 1993 IEEE International Symposium on Electronics & the Environment,* Arlington, VA. May 10-12, 1993.

Institute of Electrical and Electronic Engineers. *Conference Record of 1994 IEEE International Symposium on Electronics & the Environment,* San Francisco, CA. May 2-4, 1994.

Institute of Electrical and Electronic Engineers. *Conference Record of 1995 IEEE International Symposium on Electronics & the Environment*, Orlando, FL. May 1-3, 1995.

Kleiner, Art, "What Does it Mean to Be Green?", *Harvard Business Review*, July-August 1991.

Lenox, Michael, and Ehrenfeld, John R., "Design for Environment: A New Framework for Strategic Decisions", *Total Quality Environmental Management*, Summer 1995.

Masters, Gilbert M. Introduction to Environmental Engineering and Science. Englewood Cliffs, New Jersey, 1991.

Owens, William J., "Discussion paper on LCA impact assessment category feasibility", ISO/TC 207/SC 5/WG 4, International Standards Organization, May 1995.

Sheng, Paul S. and Srinivasan, Mukund, "Multi Objective Process in Environmentally - Conscious Manufacturing: A Feature Based Approach," ESRC Report 94-5, University of California at Berkley, 1994.

Sheng, Paul S., Dornfeld, David, Worhach, Paul, "Integration Issues in 'Green' Design and Manufacturing", ESRC Report 94-4, University of California at Berkley, 1994.

Sheng, Paul S., Worhach, Paul, Gune, Prasad, "A Network Optimization Framework for Environmentally-Conscious Process Planning and Product Design", ESRC Report 94-3, University of California at Berkley, 1994.

Society of Environmental Toxicology and Chemistry (SETAC). A Technical Framework for Life-Cycle Assessment. Pensacola, FL, January 1991.

Ulrich, Karl and Eppinger Steven, Product Design and Development, McGraw Hill, 1995.

U.S. Congress, Office of Technology Assessment, Green Products by Design: Choices for a Cleaner Environment, OTA-E-541 (Washington, DC; U.S. Government Printing Office, October 1992).

United States Environmental Protection Agency. *Life Cycle Design Guidance Manual: Environmental Requirements and The Product System.* EPA/600/R-92/226, Washington DC, January 1993.

8. INTERNET RESOURCES

A Guide to Environmental Resources on the Internet *http://www.envstudies.brown.edu/environ/documents/envguide.html*

Consortium of Green Design and Manufacturing (CGDM) Home Page, U.C. Berkeley *http://euler.berkeley.edu/green/cgdm.html*

Environmental Resources - Starting Points and Listings *http://www.fishnet.net/~scottj/envres.html*

Environmental Software Products *http://www.fishnet.net/~scottj/enswtop.html*

Environmentally Conscious Design for Manufacturing (ECDM) Infobase *http://ie.uwindsor.ca/other_green.html*

Federal Environmental Legislation and Regulations *http://www.fishnet.net/~scottj/fedleg.html*

ISO 14000 STANDARDS *http://www.iso14000.com/scs/ISO14000intro.html*

Microelectronics Computer Consortium's (MCC) Environmental Programs *http://www.mcc.com/env/*

Nortel Habitat *http://www.nortel.com/english/environ/habitat.html*

Appendix I: Company/Sector Reports

Part I: Company/Sector Introductions

Motorola (http://www.motorola.com/)

Automotive and Industrial Electronics Group (AIEG)

Part of the Automotive Energy and Controls Group that designs and manufactures a broad range of electronic components, modules and integrated electronic systems and products for automotive, industrial, transportation, navigation, communication, energy systems, consumer and lighting
markets.

AECG includes the following groups and divisions:

Automotive and Industrial Electronics Group
Component Products Group
Energy Products Division
Flat Panel Display Division
Indala Corporation
Motorola Lighting, Inc.

Government and Space Technology Group (GSTG) *(URL:http://www.motorola.com/Financial_Data/Annual_Report/1995/ataglance.html)*

Specializes in research, development and production of electronic systems and products for U.S. government projects and commercial business. The group's Satellite Communications Division is developing the IRIDIUM; satellite-based communication system.

GSTG is composed of three divisions:

Diversified Technologies Division
Government Electronics Division
Satellite Communications Division

Land Mobile Products Sector (LMPS) *(URL:http://www.mot.com/LMPS/)*

Motorola's Land Mobile Products Sector (LMPS) is one of the world's leading providers of analog and digital two-way voice and data radio products and systems for conventional, shared and private applications worldwide.

LMPS, headquartered in Schaumburg, Illinois, has manufacturing, product design, sales and service facilities throughout the world. Major manufacturing facilities are located in Dublin, Ireland; Arad, Israel; Penang, Malaysia; and in the United States in Plantation, Florida, Schaumburg, Illinois and Mt. Pleasant, Iowa.

LMPS is comprised of five worldwide business groups:

Radio Network Solutions Group (RNSG)
Radio Products Group (RPG)
Integrated Dispatch Enhanced Network (iDEN) Group
Radio Parts and Service Group (RPSG)
World Wide Network Services Group (WWNSG).

Semiconductor Products Group (SPS)
(URL:http://www.motorola.com/Financial_Data/Annual_Report/1995/ataglance.html)

Designs, produces and distributes a broad line of discrete semiconductors and integrated circuits, including microprocessors, RF devices, microcontrollers, digital signal processors, memories and sensors

SPS consists of the following groups:

Asia-Pacific Semiconductor Group
Communications, Power and Signal Technologies Group
European Semiconductor Group
Logic and Analog Technologies Group
Microcontroller Technologies Group
Microprocessor and Memory Technologies Group
Semiconductor Products Division, Nippon Motorola Limited
Communications and Advanced Consumer Technologies

Corporate (Motorola University, Corporate EHS, Corporate Manufacturing Research Center)

United Technologies (http://www.utc.com/)

United Technologies is a $23 billion corporation that provides a broad range of high-technology products and support services to customers in the aerospace, building and automotive industries worldwide. UTC's best-known products include Pratt & Whitney aircraft engines, Otis elevators and escalators, Carrier heating and air conditioning systems, Sikorsky helicopters, Hamilton Standard aerospace systems and UT Automotive components and systems. The corporation also supplies equipment and services to the U.S. space program.

Otis Corporation (http://www.otis.com/)

Otis is the world's largest elevator company, with over 50,000 employees in more than 1,700 worldwide locations. A U.S. $4.6 billion organization, Otis sells, manufactures and installs over 33,000 elevators and escalators annually, and its mechanics and agent representatives maintain in excess of 700,000 elevators and escalators in virtually every country of the world. It has more than 1.2 million elevators in operation globally, on behalf of approximately 370,000 new-equipment and service customers. Otis is a fully owned subsidiary of United Technologies Corp.

UT Automotive (http://www.uta.com/)

UTA develops, manufactures and markets a wide variety of systems and components for automobile and light truck original equipment manufacturers around the world. Electrical components and systems make up about 75% of UTA's overall business and interior trim about 25%. The company's products are part of nearly every passenger vehicle built in North America and Europe

Hamilton Standard (http://www.hamilton-standard.com/)

Hamilton Standard, a division of United Technologies Corporation, is headquartered in Windsor Locks, Conn. In addition to the NASA space suit shown on our home page, the company designs and manufactures four core product lines: engine control systems, environmental control systems, propeller systems and flight systems. Other Hamilton Standard products include commercial fuel cell power plants and advanced optical systems. Its products serve the commercial, military, regional, general aviation and space markets.

Pratt and Whitney: (http://www.utc.com/PW4000/aboutpw.html)

Pratt & Whitney, a unit of United Technologies Corporation, is a world leader in the design, manufacture and support of dependable engines for commercial, military and general aviation aircraft and space propulsion systems. Giving airline customers the best value possible is Pratt & Whitney's highest priority. It means providing the best product quality and the most comprehensive support-time and time again. This is a tradition that Pratt & Whitney has practiced proudly since 1925, starting with our first Wasp radial piston engine and evident now in our most powerful commercial turbofan engines-the PW4000 family. It is this tradition that ensures Pratt & Whitney's leadership in aerospace and propulsion technology well into the 21st century.

Sikorsky: a leading manufacturer of helicopters and parts

Part II: Company/Sector DfE Reports

AIEG - Automotive and Industrial Electronics Group

DfE Projects

The design for environment activities at AIEG were initially driven by proactive measures to get ahead of foreseeable regulatory and customer requirements. The primary customer for this group is the automotive industry. As the automotive industry focuses on improving the environmental impact of their products, this shift in focus is felt by their suppliers. For example, the automotive companies are beginning to make requests that certain chemicals or materials not be used in a product; examples are lead, PCB's and cadmium. AIEG already had programs in place to consider alternative designs and/or material choices.

AIEG is furthering these programs through the implementation of a pollution prevention program. They have added a pollution prevention coordinator who is responsible for the discovery, implementation and support of pollution prevention efforts at the various sites. These pollution prevention efforts are focused on several areas:

- transport packaging
- recycling
- reuse
- participation in product and process design reviews

Many of these efforts have been successful because they are linked to the Total Process Improvement teams. The TPI teams are focused on process improvements that result in source reduction, reutilization of materials and material substitutions, all leading to cost reductions. By showing the economics of environmental improvements, engineers and managers have an easier time supporting the DFE efforts. For example, the group has been able to demonstrate that reducing packaging and/or using returnable shipping containers for products can result in positive cost benefits, as packaging is usually a significant part of the cost for the sensitive parts.

In addition to the TPI teams, AIEG has a large recycling program under development at their manufacturing sites. In fact, at one site they have been able to earn over $700,000 in two years through recycling efforts. The efforts include recycling paper products, packaging and electronic components. These efforts have won this site the Motorola CEO EHS award for its work on recycling. There is currently an effort underway to duplicate these efforts at other Motorola sites.

As part of their pollution prevention effort, product and process design teams include the pollution prevention coordinator in their design reviews. The design reviews are a forum to present a concept to an experienced, multi-functional group of engineers and get some feedback. Including the pollution prevention coordinator in this process allows for a product or process to be improved from an environmental perspective early in the process rather than after it already has been designed. This approach has resulted in substitutions for various hazardous materials and improvements in transport packaging. Eventually, their goal is to formalize this process by including environmental reviews within the product development guidelines.

DfE Policy

AIEG's approach is to focus more on process than product. They believe that from a product perspective their designs have been environmentally favorable and they are satisfied that the product will have a minimal environmental impact at the end of its useful life. This is due to the use of components made from materials which can be shredded when the car reaches the end of its life. Therefore, their focus on process improvement.

DfE Training

About one year ago, Motorola University introduced a one-day DfE training course (SAF354) that AIEG adopted and now requires of all engineers, controllers and purchasing personnel. However, the exercises for the course were very time-consuming and the benefits were a minimal increase in awareness. As a result, AIEG took it upon themselves to redesign and consolidate the course to a half-day. The class was then promoted as a DfE awareness course and has been reasonably well received in the manufacturing plants.

DfE Tools

Currently, no specific tools are being used to help designers with DfE activities. The group is waiting to see how the Tiered Tools under development evolve. However, the marking standards developed by the LMPS sector are being implemented.

DfE Research

No specific research is underway in the area of DfE.

GSTG - Government and Space Technology Group

DfE Projects

The DfE efforts at GSTG are influenced mainly by its largest customer the U.S. government. The government has two main requirements that have influenced GSTG:

1. Government Contracts Requirements - Companies are often required to certify that the materials and process choices are based on minimizing environmental impact. Contracts sometimes prohibit, ban or restrict the use of materials. Other contracts require an analysis of environmental impact minimization.

2. Federal Acquisition Requirements (FAR's) - These rules that apply to federal purchasing. The authority for requiring "environmentally preferable and energy-efficient products and services" derives from several sources:
    - RCRA, 42 USC 6901
    - Pollution Prevention Act of 1990, 42 USC 13101
    - Executive Order 12873, 10/20/93
    - Executive Order 12856, 8/3/93
    - Executive Order 12902, 3/8/94

    A subset of FARs is Defense FARs which impose similar requirements on purchasing materials and services for defense purposes.

Although both requirements are non-specific and open-ended, GSTG is making efforts to incorporate these concerns into its product development process.

GSTG is meeting these customer needs by providing information for designers, to help them integrate environmental considerations into the product design process. Currently, GSTG has a formal design review process that includes an environmental section. This section requires that environmental considerations be taken into effect during the development process. In order to help designers meet these requirements, GSTG is developing an environmental design manual.

The design manual will serve as a reference manual for designers to use during the product development process. The design manual is specifically referenced in GSTG's standard policy and procedures for product development. The design manual is based on the Tier 1 matrix tool - based on the Tiered methodology, developed by the Corporate Manufacturing Research Center. The following are used as needed as references

- Office of Technology Assessment 's (OTA) Guide to Green Products by Design - provides designers with "general rules of thumb" for green design
- EPA's Chemical Hazardous Evaluation for Management Strategy - helps in evaluating the potential hazards of various chemicals

The manual provides reference material for a designer to help in addressing various environmental considerations. The design manual will be updated as more reference material becomes available.

In addition, GSTG is meeting DfE goals through its efforts in the area of Toxic Use Reduction. GSTG has a Toxic Use Reduction team at GSTG consists of various environmental experts, supplier representatives, chemical operations representatives and manufacturing engineers. The team has started a project designed to require suppliers to use marking standards to identify materials. This project is planned for implementation in 1996. This is part of an effort to help designers in their DfE efforts. The team is also continuing its work on other toxic use reduction projects.

DfE Policy

GSTG's 5-year strategic plan for EHS includes a sub-component that refers to DfE activities. The DfE policy at GSTG is to develop the design manual and include it as part of GSTG standard policy and procedures for new product development. This will be the first step in incorporating DfE into product design.

The next step is to ensure that the DfE policy is being followed, this will occur through the design review process referred to earlier.

DfE policy is also implicit in both corporate and GSTG policy in that it is the policy of Motorola "to respect the environment, health, and safety of our employees, customers, suppliers, and community neighbors;"

DfE Training

DfE training for GSTG is been two-fold. The first part includes the recent involvement in a pilot training class, using the Tier 1 tool developed by Motorola's Corporate Manufacturing Research Center. The pilot class involved design engineers and managers across the division. The purpose of the class was to determine the usefulness of the Tier 1 tool for GSTG. Obviously the pilot was successful, as GSTG has decided to include the tool in it's DfE design manual. Further training will involve the introduction and use of the design manual.

In addition to the Tier 1 training, GSTG has also been involved in a recent seminar conducted by Stanford University on "Business and Environmental, Health and Safety Integration" that was held for all Motorola business units. The seminar is designed to help business and EHS managers, in the following areas:

1. Use traditional business tools business analysis
2. Incorporate EHS issues in the business tools
3. Identify the business opportunity in EHS initiatives
4. Integrate EHS issues into performance management systems
5. Identify initiatives where EHS can make our business more competitive

The class focused on real-life examples of realizing the cost benefits of environmentally conscious material and process selection. A cross-section of engineering managers, proposal managers and program managers attended the seminar. Due to the success of the class, GSTG has decided to work with Stanford and Motorola University to customize the class for its own needs. GSTG is planning to make the 2-day seminar available to its managers in 1996.

DfE Tools

The design manual and the Tier 1 tool are the only tools currently under development or in use within GSTG. Other design tools will be introduced to the design groups as they become available and have been evaluated.

DfE Research

GSTG does not devote any specific funds to the area of DfE research. Any DfE research that is done, is done indirectly by engineers within product design.

LMPS - Land Mobile Products Sector

DfE Projects

DfE activities at LMPS are driven by two main factors:

1. Management Directive - Upper management continues to emphasize the importance of remaining competitive in an increasingly regulated global economy and the sector plans to enhance its environmental programs by focusing not only on compliance issues but product and process design. This directive accommodates proposed take-back legislation in Europe and efforts by competitors to design "green products".

2. Meeting and Exceeding Customer Needs - Customers are beginning to request information about the contents and impacts of particular products due to increasing regulations and environmental consumer awareness. As products are sold in markets all over the world, must know how to meet and exceed customer needs in order to remain competitive. LMPS is working closely with customers, especially in Europe, to understand their needs from an environmental perspective.

As a result of these drivers, LMPS is leading the way in DfE through involvement in a variety of DfE activities as described below:

- *Product Evaluation* - Within the last year, products have been evaluated to gain an understanding of where to focus product improvement efforts from an environmental viewpoint. The products were evaluated using the Tier 1 tool, developed by CMRC within Motorola. This was the first use of the tool within the corporation. LMPS has plans to use this tool on other products by the end of next year.
- *Development of Environmental Guidelines* - Guidelines have been created to aid designers in developing environmentally preferred products. The guidelines were developed by the Radio Products Group (RPG) technology group within LMPS. These guidelines provide information on restricted substances, general design guidelines to minimize environmental impact and performance characteristics on a variety of components with environmental impact and demanufacture considerations.
- *Implementation of Marking Standards* - LMPS is requiring that designers use marking standards, developed by the RPG technology group , for materials. This will help in the identification and separation of materials and parts during demanufacture and/or disassembly.
- *Development of DfE Design Tools* - LMPS is involved with the development of the Tier 2 design tool. This tool will help designers choose materials and processes that minimize environmental impact during the detail design phase of product development.

In addition to these DfE activities, LMPS is continuing enhancements in its EHS programs with development of Total EHS Management (TEM) metrics to help with continuous improvements in waste minimization, pollution prevention and accident prevention. These programs are focused at the manufacturing sites to reduce landfill, hazardous waste creation etc. Each site will have an operational group that is focused on these activities. In fact, LMPS has done an excellent job in meeting their waste minimization goals. For example the IL02 Schaumburg site has reduced hazardous waste by 60% and reduced VOM's from 90+ tons/yr. to 7 tons/yr. last two year. LMPS has recognized that focus on environmental design has to occur at the process and product level.

DfE Policy

Although LMPS has no formal DfE policy, they are actively involved in the area of DfE. In addition, there is an increased awareness among upper management about the importance of incorporating DfE into the business unit. In fact, upper management has proposed several metrics for the business units to report on during periodic reviews to focus the business on developing DfE programs. Management has also encouraged that DfE programs be developed by tying the development and success of the programs to the business manager's performance. This type of initiative has provided the needed incentive for the sector to pursue work in the area of DfE.

DfE Training

DfE training was the initial focus of the LMPS sector to kickoff DfE activities. Several years ago, Motorola University introduced a DfE awareness course that was taken by engineers within LMPS. The course provided some interesting and thought-provoking issues for the engineers but it didn't provide them with any tools to guide them in their everyday work. This feedback resulted in Motorola University efforts to redesign its DfE training course. In the meantime, LMPS focused on revamping the 8-hour class and customizing it for its own sector into a shorter 4-hour class. Currently, the DfE training is not a requirement for business managers or engineers.

DfE Tools

LMPS is currently focusing on the use of two tools to help with their DfE efforts: Tier 1 and the environmental design guidelines (which were described earlier). The two tools are used as part of a DfE toolset. Tier 1 is used to evaluate the product and then the guidelines are used to make improvements in products to make them environmentally preferred. LMPS is currently testing the use of these tools on several groups and based on the results will make plans to roll it out to the entire sector.

DfE Research

LMPS DfE research efforts are done through the Corporate Manufacturing Research Center and its own Advanced Manufacturing Technology Group. These groups work to develop DfE tools for designers and research alternative materials and processes that minimize environmental impact. LMPS works closely with these groups to help with development and/or implementation.

SPS - Semiconductor Products Sector

DfE Projects

The Semiconductor Products Sector has established a DFESH (Design for Environment, Health and Safety) strategy that uses input from SEMATECH. The DFESH strategy is defined as a "systematic approach to the design, manufacture, use and final disposition of semiconductors that incorporates considerations for environmental, safety and health concerns at the earliest possible stage". The scope of this strategy includes semiconductor process design and manufacturing operations since nearly all of the ESH impacts lie within processing and not within the device itself[1].

The main drivers for the development of the DFESH strategy are described below:

- *Compliance* - Regulatory compliance in Europe and other countries are accepting voluntary ESH programs as the basis for judging environmental compliance; this would replace the traditional command and control regulations in place today.

- *Cycle time* - This is a key measure within the manufacturing group at Motorola because it is critical to getting a product into market. If there are unexpected regulatory changes, this could delay the introduction of a new product and cause a significant loss in market share. As a result, SPS is aimed at reducing the possibility of a delay to market as a result of environmental regulations or restrictions.

- *Cost* - The reduction of operating costs is a goal for any business unit. The DFESH strategy is intended to reduce the risk and costs associated with the following areas: storage, handling, use, and final disposal of hazardous materials and wastes.

The main components of the strategy consist of a framework, an implementation plan and a development plan. The framework consists of four major areas:

1. *awareness* - In order to effectively implement the DFESH strategy, technical and non-technical personnel will require training. For example, process engineers will required an introduction to DFESH concepts and integration of EHS concerns into process design. Whereas, managers and suppliers will require training on DFESH management concepts, potential cost savings, and their individual roles in strategy implementation.

2. *tools* - Design tools includes tools ranging from simple brainstorming sessions and checklists to complex, quantitative software programs. These tools will be used by engineers and ESH personnel during process design and implementation.

3. *metrics* - This will be used to gauge the effectiveness of the DFESH strategy. The key goals of the metrics are to encourage people's abilities to recognize improvement and to elicit customer satisfaction that the company is meeting its DFESH objectives. The measurement strategy will be company-specific based on alignment with DFESH objectives.

4. *management systems* - This includes both organizational and informational resources needed to implement DFESH. The organizational resources are comprised of various functional groups and their interaction within the concurrent engineering

[1] Product design, use of the product after manufacture and final disposition are not included within the scope.

design team. The informational resources consists of the database systems that will aid the functional groups to make informed DFESH decisions. These systems will be used for both data collection and data reporting.

In addition to the DFESH strategy development, SPS has several on-going efforts that have been quite successful and will encourage the adoption and implementation of the recently developed DFESH strategy. These efforts include various EHS team activities to address DFESH issues and an electronic newsletter to report on DFESH successes. These efforts are described briefly below:

- EHS Strategy Team - A sector-wide team composed of EHS professionals. The team communicates and organizes the DFESH activities within various organizations and shares major learnings.
- EHS Summit - A semi-annual 2-day meeting that brings together all FAB process engineer and EHS professionals to tackle major ESH issues within the sector.
- EHS task-force - A quarterly meeting of high-level managers to discuss the direction of ESH within the sector.
- Newsletter - An quarterly electronic newsletter named Enviro-Technica that publishes articles on the DFESH successes within various FABS. Newsletter is distributed to EHS professionals and process engineers.

DfE Strategy/Policy

The DFESH strategy is in the process of being finalized and will be documented and released to the SEMATECH companies by December 1995. The strategy will be updated on a semi-annual basis by the SPS sector. Within SPS, the communication of this strategy has been ongoing. The strategy is focused at the development group with the sector because they are primarily responsible for any new process designs. However, the strategy is being communicated to EHIS managers FAB managers. In addition, various functions such as engineering, development and manufacturing technology, have been involved in the development of the strategy. This multi-functional involvement has made the acceptance of this strategy more acceptable at all levels in the organization.

DfE Training

Currently, there is no formal DFESH training that is required. However, awareness seminars about the DFESH strategy have been shared throughout the sector and four DfE training courses are being pilot tested. As described earlier, specific DFESH training for strategy implementation will vary depending on functional group. Efforts are underway to develop the training. For example, as the tools for DFESH are developed they are tested by designers and engineers.

DfE Tools

There are several types of tools that are currently under development: risk assessment, life-cycle costing, mass balance and design guidelines. All of these tools will be aimed at process designers in the US and Europe. The tools are described below:

- CARRI: Risk Assessment Model - CARRI is a computerized risk ranking tool that provides a consistent method for engineers and managers in the semiconductor industry to evaluate alternative chemicals and processes to determine their relative ESH impacts. The tool evaluates the risks by assessing both the inherent hazard properties of the chemicals and the potential for exposure to the chemicals. The relative impact of each process is determined using the Analytical Hierarchy Process. The tool is available with a standard set of pre-defined semiconductor manufacturing processes with the ability to define more in the future. The tool is currently being pilot tested in 2 fabs.

- Cost of Ownership - This accounting tool provides the framework for accounting activities that drive ESH costs at the manufacturing process level. This refers to accounting for direct and indirect costs, as well as tangible and less-tangible costs. This model, not only, accounts for traditional materials and operating costs but also hidden costs such as ESH management costs and cost benefits from recycling and energy efficiency improvements. Although the model is robust, there is still some difficulty in estimating some of the less-tangible costs. The model is best utilized by technical staff who are aware of ESH problems but are unsure of the magnitude of the economic impact. This tool is developed specifically for SEMATECH Member Companies.

- Materials/Energy Balance - This tool will allow an engineer to complete a mass energy balance at the process and factory level. The user will provide specific input information, and the tool will determine the process output (or emissions). The model will help to track total emissions of a compound in the facility for permitting purposes or waste generation information. This tool will be available for SEMATECH members in 1997.

- Process Design Matrix - The matrix tool is based on the Tiered Approach developed by the Cooperate Manufacturing Research Center at Motorola. The tool enables a semi-quantitative life cycle assessment without having to complete a life cycle inventory and assess each and every ESH concern. The process matrix is designed to assist in the evaluation of materials choice, energy use, solid residues, liquid residues and gaseous residues for various life cycle stages. This tool is being pilot tested in two fabs.

The goal is to eventually link all of the materials/energy balance and Cost of Ownership models with the CARRI risk assessment tool to provide a more robust tool. This integration of the tools will facilitate a complete ESH evaluation of design alternatives by allowing the tools to share data and perform evaluations simultaneously. The ALCA Matrix will provide process engineers an overall assessment tool that can be used during the various phases of process development.

DfE Research

The DfE research activities that Motorola is involved with are supplemented by SEMATECH projects. Motorola currently funds SEMATECH and therefore leverages their resources. The research activities include the development of DfE Tools, Metrics and Training.

Motorola Corporate

Corporate Manufacturing Research Center, Motorola University, Corporate EHS

DfE Projects

Motorola has many DfE activities underway at the corporate level. This increase in DfE activities is the result of pollution prevention regulation, proposed European Take-Back legislation and customer requirements for "greener products". Motorola realizes that in order to remain competitive in a global marketplace, environmental considerations must be addressed during product and process design. A brief description of some of the DfE activities Motorola is involved in are described below.

1. Benchmarking - Motorola is continually involved in investigating DfE activities world-wide. Motorola has done several benchmarking studies within the electronics industry to gain perspective on DfE activities and focus their own DfE efforts.
2. Take-Back Task Force - This group was developed to address the proposed European Take-Back Legislation and to devise possible take-back schemes for the product groups. This group is mainly composed of business managers and EHS managers from Europe. The group has developed a strategy and is currently developing an action plan.
3. ISO 14000 Development - Motorola is involved in the development of the ISO standards, with specific focus on environmental management standards **(EMS)**, EMS auditing, environmental labeling and life-cycle assessment standards. Appropriate revisions to internal EHS standards are being prepared in anticipation of market driven demands for conformance to the ISO 14001 EMS Specification.
4. Pollution Prevention Activities - Efforts are continuing in the area of pollution prevention at the manufacturing sites. Many sites have incorporated pollution prevention into their business plans and are employing metrics to measure its success. Many sites have used the TCS (Total Customer Satisfaction) Team concept to empower employees to implement pollution prevention programs. Motorola's EHS Standards require that sites establish pollution prevention plans for their operations. In addition, Motorola is active in voluntary US EPA programs such as WasteWi$e and 33/50.

These activities represent only a few of the DfE activities going on at Motorola. The corporate group serves as support for the business units. The business units are responsible for deploying DfE.

DfE Policy

There is currently no corporate policy that requires DfE. However, Motorola does have a Take-Back Strategy that is currently under development. In addition, corporate EHS is beginning to develop goals that focus on DfE activities.

DfE Training

Motorola University is the primary source of training for the company. In general, the courses developed for DfE have been given in the US operations and not abroad. Over the past few years, they have introduced several DfE type training classes. Most of the classes have been focused on awareness training. However, a self-paced class has been developed. This class provides designers with the DfE tools necessary to employ DfE within the design process. A description and status of the classes is given below.

SAF 352 (Protection of Our Environment)

A general purpose awareness course to heighten awareness of environmental issues facing the company. CEO supports the class and had made it mandatory for all Motorolans.

SAF 354 (DfE Course I)
A course designed for engineers to help in addressing Design for Environment issues. Course was not marketed correctly and as a result, the course did not meet designers expectations for tangible tools to help in DfE efforts. As of May 1996, approximately 1000 engineers have attended.

SAF 357
This course was developed within last three months and targeted at management. The course was developed to get "buy-in" of management for DfE programs. The direction for this course was given by the EHS Executive Council. The course is not mandatory, as of today a few hundred have attended.

Matrix Approach to DfE
Three courses based on the Tiered Methodology developed in the CMRC group at Motorola have been developed. The Methodology is series of tools defined for various points in the design process. The courses focus on the Tier 1 tool, which is aimed at the concept development phase. The tools for process and product have been designed separately. The courses are self-taught and are available via the World Wide Web.

DfE Tools

At the corporate level, there is a tool development effort underway at CMRC. The two tools that are being developed are based on Tiered Methodology. The tools are described below:

- Tier 1 - A matrix approach is used to ask questions of the product at the concept development phase of product development. The questions are general leading to specifications and design rules which will broadly shape the direction of the new product.

- Tier 2 - A tool designed to help designers reduce the environmental impact of components during the detail design phase of product development. The tool provides a quantitative measure of the various design choices available to a designer. The measures are based on material and process choices.

DfE Research

The majority of research done in the area of DfE at Motorola is directed through the CMRC Environmental Technology Group. Motorola is involved in participating and funding several DfE activities, several are described below.

1. Demanufacturing - working with Carnegie-Mellon University on a demanufactuing assessment
2. Disassembly - funding work at Georgia Tech to develop tools for automated disassembly
3. Life Cycle Analysis (CMRC) - dedicated resources within Motorola to explore LCA methods and perform LCA's at Motorola
4. MicroElectronics Computer Consortium - partnership with MCC to develop a road map for DfE and a take-back study in the electronics industry; consortium includes companies such as Texas Instruments

Hamilton Standard

DfE Projects

Technical Standard 0300 (TS0300) is the basis of most DfE efforts within Hamilton Standard. It is essentially a material substitution guideline that was developed to aid designers in selecting materials and processes that minimize the generation of wastes listed on the EPA's 33/50 list. The guidelines include a list of the commonly used specifications that should be avoided and possible replacement processes.

Various Engineering Systems Manuals (ESMs) include requirements for Environmental Compliance Reviews (i.e. TS0300 reviews). The cognizant Project/Development Engineer must perform the review at specified times in the design process and certify TS0300 compliance with their signature. In practice, engineering drawings include a signature box that certifies the TS0300 compliance of all new designs and design changes.

TS0300 compliance may be obtained even if specified materials are used provided a "good, sound reason" exists. Seven such reasons are defined by the Standard:

1. Economic Impact - the alternative would make an existing product totally non-competitive
2. Software changes do not require redesign for TS0300 compliance.
3. Development tests - no production is planned
4. Performance - the alternative does not perform adequately to meet service/qualification test requirements
5. A new design that incorporates subsystems that are not in compliance
6. The hazardous material generating material/process is a contractual requirement
7. Adequate waste treatment facilities are in place to process/treat/recycle the hazardous waste and there are no cost effective alternatives

Hamilton Standard's DfE program also requires that a tracking system be utilized to identify applications where TS0300 is not being met. This allows for prioritization of R&D, education and the investigation of alternatives. Additionally, tracking TS0300 compliance generates an effective metric for measuring the improvement of their products.

The data collection portion of this program has not yet been implemented. TS0300 is in use, but the tracking forms are not required or collected.. A training program was developed in early 1994 but never authorized due to resource constraints. There has been no change in the status of this project since approximately April of 1994[2].

[2] Interview with Blair Smith, Hamilton Standard Materials Engineering Group

DfE Policy

Hamilton is involved in the development of a corporate wide DfE policy statement. That statement is included in the appendix. Within Hamilton, DfE policy has taken the form of statements in four ESM documents:

1. ESM 3211 - "Approval of Engineering Documents"
2. ESM 3220 - "Revision to Engineering Documents"
3. ESM 3221 - "Engineering Change Form"
4. ESM 3222 - "Proposal for Engineering Change"

These documents require that TS0300 compliance be certified as part of the design process. The exceptions listed above are permitted by each of the ESM's.

DfE Training

Considerable effort was expended in developing a DfE/TS0300 training class for use throughout Hamilton Standard. The Materials Engineering group developed a two hour class that included case studies and an exercise in evaluating TS0300 compliance. The course was intended to introduce TS0300 and specifically the compliance tracking system to all designers within Hamilton Standard.

The class was not yet been presented to Hamilton Standard's designers.

DfE Tools

TS0300 is the only DfE tool currently in use or under development within Hamilton Standard. Interviews with designers and materials engineers revealed a desire for tools:

1. A material and process selection database
2. Material inventory tracking system
3. Tool that brings material guidelines into the CAD system
4. Automated tracking of TS0300 compliance and exception justification information

DfE Research

Hamilton Standard does not have resources specifically available for research either in DfE methodology or environmental technology. Funding for the current research on material substitution comes from the operating units that require the alternative technology.

Otis

DfE Projects

The focus of the EH&S department is largely in the area of safety. Many product changes are being made with the objective of making the equipment safer to operate and maintain. Otis is gaining valuable experience for understanding how the product design process can be adjusted to include the consideration of "new" variables. This knowledge will be very useful when Otis begins working on DfE. Other UTC companies should approach Otis and learn from their work in Design for Safety.

Otis has made product changes in the name of improved environmental performance. Specifically, Otis is introducing a new, roped hydraulic, elevator in 1996. This elevator will improve environmental performance by moving the cylinder above ground so that leaks can be more easily detected, contained and repaired. The elevator is based on a European design used for several years that is now being made a global design standard.

Otis has also completed small projects in such areas as powder painting and hydraulic fluid replacements. These projects tend to be small, usually applying to only one of Otis' 50+ independent companies.

DfE Policy

Otis' Policy 9 is titled "Statement of Environmental Policy." One section of this policy applies to DfE and product stewardship.

> *"Otis will conduct its operations and design its products in a manner to control emissions, discharges and wastes and to enhance health safety and general welfare."*

This statement implies that Otis accepts a total life cycle view of product stewardship. There are no other policies at Otis that focus specifically on DfE.

DfE Training

Otis has conducted extensive training in design for safety. This experience will be useful in developing a more broad based DfE training in the future.

DfE Tools

There are no DfE tools in use or development at Otis. LCA development being done at the UTRC may, one day, be adopted by designers at Otis.

DfE Research

Otis has resources budget for centralized research into design for safety. Broader based DfE research is fragmented, usually conducted as small, independent efforts. Their is no budget for centralized R&D into environmental technology.

Pratt and Whitney

DfE Projects

The Consolidated Pollution Prevention Team (CPPT) oversees and coordinates the work of three other teams tasked with improving the environmental performance of Pratt and Whitney products. The mission of the CPPT is:

> *"Establish and maintain a unified Pratt and Whitney Pollution Prevention strategy as a key factor in the production and support of our product. Create and maintain awareness at all levels, establish reduction goals and set direction for the other pollution prevention teams[3]."*

They approach this mission mainly through the generation of policies and "standards of use" that create the rules to be followed by Pratt and Whitney's design and manufacturing personnel. The CPPT takes input from upper management, the customer, regulations and corporate EHS when crafting a new standard. Once completed, the standards are released to the Waste Elimination Steering Committee (WESC) and the Environment, Health and Safety Design Team (EHSDT) for dissemination and implementation.

The Waste Elimination Steering Committee (WESC) communicates the standards to Design Team and then onto the product centers and the Charter Part Councils. Each product center is required to have a Pollution Prevention Plan that identifies the major waste streams and a plan to eliminate them. The WESC ensures that the plan meets the requirements specified by the CCPT's policies and monitors the progress of the each product center in carrying out their Pollution Prevention Plan.

The Environment, Health & Safety Design Team (EHSDT) determines which of the Charter Part Councils[4] and which products have parts affected by a standard. (Here is where the communication to the CPCs occurs.) They then generate a list of part numbers and identify alternatives for each application. The CPC is encouraged to revise its specifications to improve environmental performance. Applications where no good alternative is available are referred to the Environmental Technology Team (ETT) for technical assistance.

The ETT serves as a technology consulting resource for the other teams. They examine standards (from the CPPT or the CPCs) and identify areas where research is needed or the standards require revision. The ETT also helps to locate funding for environmental technology development programs.

Currently, these teams are very active within Pratt and Whitney.

1. The WESC is very active in organizing and conducting environmental "Kaizan Events." These week long activities have resulted in considerable reductions in the amount of hazardous materials used within several manufacturing plants.

[3] Presentation given by Matt Falco of Pratt and Whitney, 15 June 1995.

[4] Charter Part Councils exist for each major family of parts. They set the technical specifications that must be observed by designers working on parts in the family. CPCs determine materials, coatings, treatments, and process that can be used in creating the parts. They typically consist of several experienced designers who meet periodically to determine technical specifications.

Operators, engineers and designers are encouraged to "Walk the Process" together to identify ways that waste can be eliminated.

2. The EHSDT is examining new designs for the use of hazardous materials. They have taken a leadership role in identifying opportunities for material and process substitution. The emphasis on new products stems from a belief that it is easier to prevent the use of certain materials than it is to revisit and re-certify proven designs.
3. The ETT is working on eliminating the technological barriers to environmental improvement. Research is currently focused on identifying replacements for cadmium and others.

In addition to the work of the pollution prevention teams, Pratt and Whitney continues on-going projects to improve fuel efficiency and to reduce emissions. These two areas remain major marketing points in the jet engine business in addition to being environmental issues.

DfE Policy

Pratt and Whitney is involved in the development of a corporate wide DfE policy statement. Within the business unit, DfE policy has taken the form of the goals developed by the CPPT. These include:

1. Elimination of the use of all halogenated chemical usage by 12/96
2. Elimination of lead containing antigallant usage by 12/96
3. Elimination of cadmium containing coatings usage by 12/97
4. Compliance with NESHAP[5] regulated high VOC coatings

Certain new product development efforts are being given DfE objectives. These take the form of hazardous material content goals, specifically that the engines be cadmium and lead free. These goals are in reaction to marketing pressures more than scientific environmental information.

DfE Training

A one-time DfE class was given to all design engineers within Pratt and Whitney. Its purpose was to introduce DfE concepts, the major environmental concerns, and the available resources to the engineers. The class was intended to convey the idea that DfE is the responsibility of each engineer, not just the EH&S specialist. The class is not a regular part of Pratt and Whitney's training program.

The DfE class was generated and taught by the EHSDT. It included a lecture and a case study and lasted for 30 minutes. Design engineers of various disciplines took the class, however, there are no plans to revise the class or repeat the instruction.

DfE Tools

Pratt and Whitney is active in the use and development of DfE tools. Several of the tools are very mature and have been in use for many years. These tools are generally not recognized as "DfE" because they address the traditionally competitive issues of fuel efficiency, emissions and engine noise.

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[5]NESHAP - National Emission Standards for Hazardous Air Pollutant

More recently, tools are being developed to aid designers in making material choices and for estimating the total life cycle cost of the engines. These tools are being developed in response to changing customer requirements. Specifically, the use of the 17 substances on the EPA's 33/50 list is being shunned by the military and some civilian customers. Pratt and Whitney's response has been the development of a material selection guide[6] to assist designers in identifying replacements for the non-preferred materials and processes. These guidelines are very similar to those developed by Hamilton Standard.

Pratt and Whitney is involved in the development and use of life cycle costing tools as well. Also, a tool called HAZMAT is being used to quantify the life cycle costs of using hazardous materials in processes. The hope is that by identifying the true costs associated with the use of these materials, alternatives that are both less expensive and environmentally preferred will be chosen.

Surveys revealed that designers and EH&S representatives would like new DfE tools. Specifically, they identified tools for: Disassembly, Cost Analysis, and Multi-Variable Decision Making as crucial for improving DfE efforts. While work continues on the Cost Analysis tools, nothing was identified in the other two areas mentioned.

DfE Research

The Environmental Technology Team manages research in product environmental performance. Pratt and Whitney has partnered with the United Technologies Research Center, the US Military, and the NDCEE[7] for work on developing environmental technologies. Current areas of interest include: substitutes for cadmium plating and lead antigallants, chromic acid anodize replacements, compliant paints, NOx reduction, and fuel efficiency. There is no known research in DfE methodology. The projects are funded mainly through the ETT which is funded in turn through Operations. Some projects are funded by Engine Model Groups and when possible, funding is leveraged with industry partners.

[6] Environmental Considerations for Integrated Product Design, published by Pratt and Whitney's Environmental Design Team.

[7] National Defense Center for Environmental Excellence

United Technologies Automotive (Europe)

DfE Projects

Heightened customer awareness of environmental issues in Europe has translated to specific demands on the products of UTAE. Saab and Volvo are interested in component Life Cycle data while Reneault and Opel are focusing on recyclability and the possibility of product take-back legislation. Customer concerns have led UTAE to adopt the belief that providing environmental performance information can be a marketing advantage today and may be a necessity in the near future.

UTAE has responded to customer pressure in several ways. They have modified designs to meet specific requests. An example is the replacement of PVC tape with a textile tape for Saab, Volvo, and Rover wiring systems projects. They also conform to rigidly defined weight requirements designed to reduce fuel consumption (and therefore emissions).

UTAE has teamed with the United Technologies Research Center (UTRC) to explore a proactive approach to DfE as well. Specifically, a project is underway to introduce basic LCA tools to the design centers in Europe. The project is intended to allow UTAE to provide its customers with Inventory and Impact analysis of products for their vehicles. Although no customer has yet demanded such information, UTAE believes that it is inevitable and that early adoption will give UTAE a marketing advantage. UTAE also views this project as preparation for ISO14000 and EMAS[8] certification and the demands that will be placed on automotive suppliers.

UTAE and UTRC have chosen SimaPro as the LCA tool for the design centers. The tools includes a partial library of common engineering materials and processes. It also includes energy and disposal scenarios for Europe. The program allows designers or analysts to view environmental impact in several different ways. The designer will want to compare the impact of two possible design alternatives. She may also wish to "dig down" and discover what aspect of the design is causing poor environmental performance. SimaPro allows these types of comparisons. Additionally, SimaPro gives the analyst detailed inventory information; what is released, how much, and from which processes.

There are several reasons for choosing a commercially available LCA package as opposed to developing the data collection technology in-house:

1. Rapid Deployment: Using a commercial database gives UTAE the advantage that it has much more information available, more quickly, than if it was forced to complete the data collection itself.
2. Reduced Liability: When dealing with environmental issues, the problem of liability is very important. Using third party data reduces suspicion and integrity questions that might otherwise be raised by customers (or environmental groups) that review your work.
3. Economics: Without question, a commercial LCA package and database gives UTAE the ability to get and maintain current data for much less than it would cost to develop a system internally.

[8] European Eco Management and Audit Scheme (http://www.quality.co.uk/emas.htm)

DfE Policy

UTAE environmental policy mainly focuses on compliance and worldwide standardization in EH&S management practices. Local customer requirements often determine the environmental features of UTAE products. This means that DfE policy is essentially set by specific customers and European legislation. The corporate European EH&S staff's efforts to promote the introduction of the LCA tool appears to be a notable exception to this. Moving beyond customer requirements would allow a UTAE-wide, DfE policy to develop.

DfE Training

The UTRC/UTAE Environmental Tools (LCA) project began with a short introduction to LCA and DfE methodologies. The class was broken into two phases for the wire harness business:

- Phase I: The UTRC team gave a presentation providing general environmental background, industry trends, and information on LCA tools. Special emphasis was placed on how these tools can be used to improve designs and to create a competitive business advantage. This phase has been completed at all of the UTAE design centers in Europe.
- Phase II: Design engineers use SimaPro and simple spreadsheet models to learn by example how to use the software to improve and evaluate their products. Phase II coverage is limited to approximately 3 engineers per design center.

There are no plans to expand or repeat the training program. The intention instead is, that the engineers who have been identified as "site DfE champions" will conduct training within the design centers. Also, a goal for 1997 is to extend the capabilities for environmental design developed in the Wiring Systems division to the other UTAE businesses.

DfE Tools

SimaPro is the only DfE tool currently in use or under development on a UTAE-wide basis. UTAE-Spain makes limited use of recyclability guidelines developed by their customer (Opel). Interviews with designers and materials engineers revealed a desire for tools:

1. A material and process selection database
2. Improved LCA capabilities (data and interface)
3. Methods of Aggregate Analysis
4. Consistent recyclability guidelines

DfE Research

UTAE Headquarters continues to support DfE research implemented through UTA's globally integrated technology program. Funding for the current research on the use of recycled materials (Spain), and LCA software, comes from a centrally planned R&D budget.

Sikorsky

DfE Projects

Sikorsky's DfE work centers on a large material inventory program contracted by the Army as part of the Commanche development program. Together with Boeing, Sikorsky was paid approximately $2 million for the study. This effort represents the first time that a material inventory was attempted on such a large and complex item. It also represents the first military aircraft development contract that included specific environmental requirements. The project was originally conceived with two phases.

Phase 1:
The first stage of the environmental program was to identify materials in each subsystem of the aircraft. Each design group was responsible for cataloging the materials and processes used in producing their respective section. This information was passed up the chain and evaluated. If more information was needed, it was requested with an emphasis placed on those materials and processes known to have toxic content. The information was then compiled into a large report and the hazardous materials were prioritized.

The first stage was performed mainly by the design teams including representatives from manufacturing, engineering, and EH&S. EH&S also conducted training for each team and served as a resource when issues arose.

Phase 2:
The second stage of the project was never funded by the Army. It was to have identified the 5 highest priority hazardous materials and investigated substitution options. The design would then have been changed wherever possible. It is unknown why the second stage was not approved.

The Army undertook this project in the name of life cycle cost reduction. The current fiscal policy has forced the military to cut costs where possible and as a result, the Army has begun considering total life cycle costs when evaluating its development programs. A representative of Sikorsky gave an example[9]:

> *"Suppose the Army decides to continue using the traditional, chromium containing paint. They really haven't just decided to use the paint in manufacturing, they've made the decision that for the next 20-30 years they are going to have a steady stream of chromium waste from their maintenance facilities. If each helicopter gets repainted every couple of years, the volume, and therefore the expense will be considerable."*

Other than the Army project, Sikorsky is also involved in a number of pollution prevention efforts. Again, no effort was made to investigate those for this paper.

DfE Research

Sikorsky does not have resources specifically available for research either in DfE methodology or environmental technology.

[9] Adam Weissman, Interview on 2 August 1995

Appendix II

Design for Environment

by Neha Shah

Development of the Design Advisor (DA) Tool[10]

I. Introduction

In today's marketplace, manufacturer's are increasingly concerned with providing customers with environmentally conscious products. This concern is influenced by such factors as: customer demand for "green" products, pollution prevention regulation, proposed take-back legislation in Europe and ISO 14000 certification. In order to meet these concerns and remain competitive, in a global market, companies need to develop tools to help consider the environmental impact of their products early within the design process.

The most widely known tool for assessing the environmental impact of a product is a Life-Cycle Analysis. Unfortunately, the analysis is quite complex and time-consuming and requires an in-depth knowledge of the entire product, which is only available during the final stages of product development. For this reason, Motorola is developing a DfE (Design for Environment) tool to aid designers during the initial stages of product development when only partial product information is available. This DfE tool, the Design Advisor, will help designers to design products that have a minimal environmental impact. The DA tool will be part of a DfE toolset, that includes a Life-Cycle Analysis during the final stages of product development.

In this paper, we focus on the initial development and application of the DA Tool at Motorola. We begin with some background on the why there is a need for the DA Tool. Next, the development and structure of the tool are described. Then, a case study is presented to demonstrate the DA concept for a specific component - EMI Shielding. Finally, recommendations for the continuing development of the tool are presented.

II. Background

During the last few years, designers have become more aware of environmental issues and their cost in the marketplace. As a result, designers want to push beyond awareness and begin to incorporate environmental concerns into their daily work. Designers and engineers are beginning to request training that provides them with the necessary design for environment tools to integrate environmental issues into the product design process.

The DA tool is based on the Tiered Methodology and Design Advisor concepts developed at Motorola. Both concepts focus on ways of providing designers with guidelines to use during the initial stages of product development. The need for tools during these initial stages is critical because this is when the key decisions that effect the ultimate environmental impact of the product are made. The traditional life-cycle analysis tools focus on providing information on a product's environmental impact after the product is completely designed. At this stage, it is difficult to change the product's make-up as many manufacturing, financial and marketing decisions are finalized based on the final design.

The Tier 1 tool, described in [Hoffman][11], provides a set of questions that a design team can use during the concept development phase to determine a qualitative measure of the environmental impact of a product. The Tier 1 tool is based on the well-known matrix approach developed at AT&T. Based on the overall score received, these questions provide a

[10] The author participated in a cross sector tool development team at Motorola, this paper is a discussion of that work.

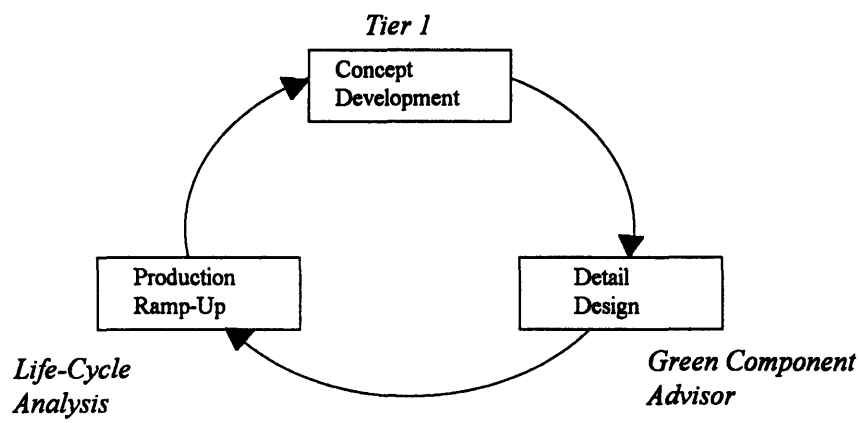
[11] Hoffman, Bill "A Tiered Approach to Design for the Environment", Corporate Manufacturing Research Center.

guide as to what "environmental" areas the team can focus on to make improvements in the product. This tool was piloted with several design teams across Motorola.

The results of the pilot demonstrated the need to develop the next tool in the design cycle: the DA tool. The designers were quite interested in the issues raised as a result of using the Tier 1 tool. But, they were concerned that the tool only provided them with a qualitative measure of environmental areas of concern but no quantitative measure to make a comparison of various design choices. The designers wanted a tool to use during the detail design stage of product development. Of course, performing a life-cycle analysis is one answer, but not enough information is available at the detail design stage. In addition, a life-cycle analysis requires an in-depth and time consuming analysis of each design choice which is not realistic for a design team, especially as development cycles become shorter and shorter.

As a result of the designer needs and the Tier 1 tool pilot, development of the DA tool began. The DA tool is another tool within the DfE toolset to provide designers with an approximate measure on the environmental impact of a product. The Tier 1 tool, the DA tool and life-cycle analysis tools are all necessary tools during the product development cycle. Each tool must be applied based on the phase of development, as shown in Figure 1. At Motorola, designers are anxious for DFE tools that provide quantitative information about design choices, thus the development of the DA tool.

Figure 1 - DfE Toolset for Product Design



III. User/Designer Needs

In order to develop an effective tool that can be implemented and used, we must understand not only what the drivers are for the tool but also what the user needs are for the tool. In the case of the DA tool, the primary users are mechanical designers. Therefore, we interviewed designers from various sectors within Motorola to gain a better understanding of what factors were important for a design tool. The following is a summarized list of the designer needs, not necessarily in order of importance:

a. *Environmental Change Effect on Bottom Line* - When a change is made in a component or product that effects the environmental impact of a product, an indication of the product cost impact should also be provided.

b. *Comparison of Environmental Impacts* - The ability to compare the environmental impact of materials, processes, and components on a quantitative level.

c. *Identification of Cause of Environmental Impact* - When a measure of the environmental impact of a product is provided, provide a simple way to understand the factors that contribute to the impact in some order of importance.

d. *Indication of Data Quality* - Each measure or score should provide some indication of the data quality. In other words, provide information of the confidence level in the data.

e. *Minimize Amount of Data Entry* - Minimize the amount of information the user has to input to the tool. User already has a variety of tools he or she has to use, don't provide unnecessary additional data entry.

f. *Indication of Minimal Regulatory Requirements* - A note or score indicating that the minimal regulatory requirements have been met for the particular component or part.

g. *Tool Platform* - The tool is developed on the same platform (i.e. UNIX) as other design tools already in use, such as Pro-Engineer.

We recognize that all of the user requirements are important to ensure the successful development and application of the tool. However, we also realize that trying to incorporate every need during the initial tool development would be impractical. After careful consideration of the user needs and the company needs, we decided to focus the initial tool development on the needs labeled b though e. We chose these needs because they are fundamental to the overall structure and development of the tool.

IV. Team Approach

An important part of the success of this tool is ensuring that a cross-section of the company is represented during the development. As Motorola is a very de-centralized company, each sector can behave as an independent company with its own goals and objectives. In addition, each sector has various functions such as: product development, marketing, finance, manufacturing, research & development. Within this type of company, if a new concept is to be successfully implemented it must have the buy-in of these various groups.

The DA tool team is cross-functional and has representatives from engineering, research and management from various sectors. This cross-functional approach gives the team the opportunity to leverage off the knowledge and experiences in various groups to make a tool that will be useful company-wide. In addition, the team provides a forum to discuss environmental issues facing a particular sector and possible solutions among company environmental "experts".

V. DA Tool Structure

The DA tool is focused on product design at the component level, or the detail design phase of product development. The components selected for this tool are based on the typical contents found in a radio product, as this can be applied company-wide. (Each team member was given assigned a particular component to focus on). The components are categorized within three main sub-assembly headings as seen in Table I.

Table 1

Components of a Typical Radio Product

PCB Assembly	**Mechanical Assembly**	**Electro-Mechancial Assembly**
Substrate Material	Housings	Pots
Attach Medium	Keypads	Switches
Components	Structural Items	Speakers
	Cells	Microphones
	Labels	
	Connector	
	Product Packaging	
	Shielding	
	Antenna	
	Cables	
	Mechanical Interface	

The structure underlying the DA tool is designed to complement the design path that the engineer follows during the course of component design. In order to design a component, the designer decides between a variety of materials and processes based on various design constraints such as cost, quality and functionality - the design scope. The unique combination of materials and processes selected will determine the make-up of the part. If the tool is to be used, it must work within this design framework.

The initial development of the tool is described in four steps:

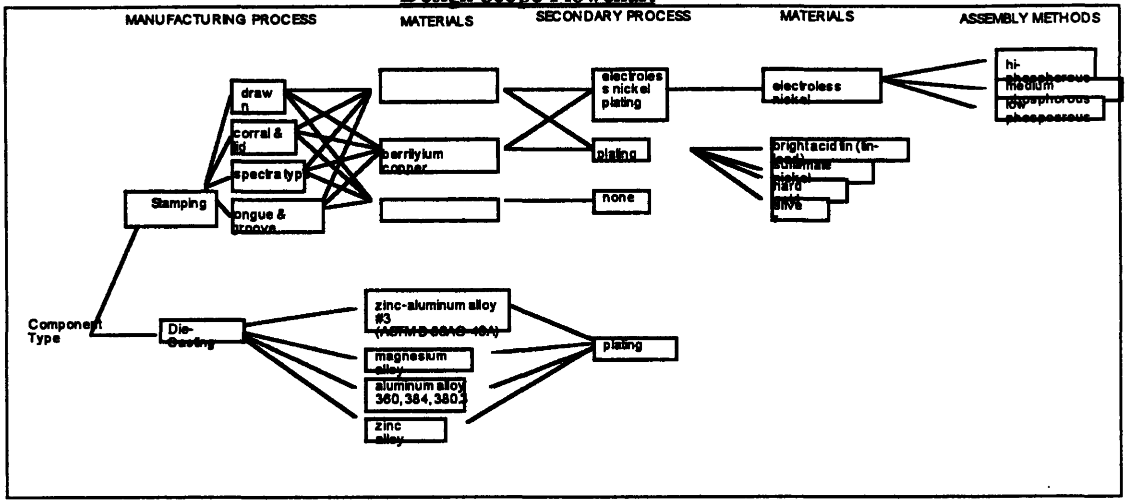
1. *Design Scope* - develop a flowchart of material and process choices for a particular for components
2. *Impact Selection* - determine which environmental impact areas of concern to company
3. *Metric Selection* - select metrics that serve as approximate measures for impact areas
4. *Scoring* - assign scores to materials and processes based on metric values weighting of impact areas

The four steps are described in greater detail below. The steps are not necessarily in chronological order, due to the fact that the tool development process is iterative.

Step 1 - Design Scope

The purpose of Step 1 is to collect information about the design scope on the various design options available for a particular component. This requires collecting data on all the material and process choices available to a designer within the company (and even outside the company). This data provides not only a list of design choices but also information on how the choices were made and what constraints limited their choices as shown in Figure 2.

Figure 2
Design Scope Flowchart



This flowchart provides information on the how the designer steps through the design choices available to him or her. The designer chooses a process and then has a limited number of materials to choose from. Then the designer may have to choose a secondary process from a limited set of choices. This makes it clear to the tool developer how the environmental scores can be applied to be meaningful to the designer within the current design framework. This step also provides information on the number of design choices available to a designer. As tool developers, this gives us an indication of whether design options exist for environmentally preferred materials or processes. In addition, this tells us how many different materials and processes we must investigate.

When defining the design scope, we must also consider the level of detail we are capturing as shown in Figure 1. Although, we want to capture the detail of the design process, we must also define the scope of this tool. Otherwise we run the risk of going too far back into the design, where the designer has little to no influence. For example, the choice as to what type of process is used to plate a material may be a decision that is made by a secondary supplier that the designer is not aware of. Therefore, we have limited the boundary for the design scope of this tool to the primary supplier.

Step 2 - Impact Selection

The next step in the tool development is to determine the basis by which the design choices, captured in Step 1, will be compared. In other words, we must determine the environmental impact areas of concern to evaluate various design choices. Impact as defined by SETAC is "any effect to human health and welfare or the environment. In this case, the impact may be defined as the reasonable anticipation of an effect"[12]. The four key categories of impact , as defined by SETAC, are: ecological health, human health, resource depletion, and social welfare.

Using the SETAC list as a guide and considering company goals and customer needs, a list of possible assessment criteria was generated. In this case, the proposed criteria were:

- product material toxicity
- manufacturing process toxicity
- recycled material content
- energy use

[12] "A Conceptual Framework for Life-Cycle Impact Assessment", SETAC, 1992.

- percent recyclable.

Based on this list, we chose three impact (or assessment areas to focus on for the initial tool development: toxicity, sustainability, and energy use. These impact areas were selected among others based on available data. In other words, we attempted to select assessment criteria where we believed data already existed. Toxicity is defined broadly to cover any toxic effects that materials or processes might have on human health. Sustainability is defined as minimizing resource use in order to provide resources for future generations. In other words, minimize the waste generated. Finally, energy use is a measure of the energy required to process a material or the energy required to use a certain process. The impacts are used to "guide" the designer in an environmentally preferred direction.

Step 3 - Metric Selection

Once impacts are chosen, then metrics are selected to relate the approximate effect that the materials and processes of a component have on an impact area. The metrics are defined as measurable quantities that serve as approximate measures of the impact area of concern. The metrics for materials and processes may differ for each impact area. The material metrics for the impact areas, mentioned in Step 2, are shown below in Table 2.

Table 2

Impact - Material Metrics

Impact	Metric
Toxicity	HMIS Score
Sustainability	Recyclability
	Remanufacturability
	Design for Disassembly
	Waste Generation
Energy Use	Heat Capacity

A single metric or combination of metrics are selected to approximate the effect a material or process has on a given impact area. The metric values for an impact area are used to compare one component relative to another. In other words, one can compare the sustainability of one component versus another but one cannot give an absolute measure of sustainability.

The metric values are determined by developing models that will approximate the metric of concern. For example, the model used to determine the recyclability value is averaging the recycle rate and recycle efficiency values which are based on industry average values. This is a simple model, however as data availability improves the models will also change and the metric value can be updated to be more reflective a more accurate value. This recyclability value is used as the measure for sustainability, as we currently have no data for the other metric areas. However, as this data becomes available, we will include these metrics values in determining an overall sustainability score.

For toxicity metric values, we use the HMIS Score as an approximate relative measure of toxicity to compare materials. The HMIS Score is based on information from the Material Safety Data Sheet (MSDS). The information is stored in a database that provides a score that factors in the health, reactivity and fire effects of a material . Ideally, the measure for toxicity would be the results of an LD50 or LC50 test for a material. The LD50 is a measure of the dose of a material that can kill 50% of the test subjects. The LC50 is a measure of the concentration of material that can cause toxic effects in 50% of the test subjects. Currently, the LD50 and LC50 tests performed vary from material to material. The tests are done on different lab animals with different material concentrations for various durations. All these differences make it difficult to compare a LD50 or LC50 result from one material to another. But eventually as more tests are done and consistent data becomes available this would be a more accurate measure of toxicity than the HMIS score.

In the case of energy use, we currently use the heat capacity and mass of a material as the measure for energy use. Heat capacity is used because it provides some indication of the energy needed to process a unit of material. Although it is not a perfect measure, it does provide a quantitative number to base the energy use score on rather than relying on expert opinion. Ideally, we would conduct our own experiments with various materials to determine the amount of energy required to incinerate or dispose of a material, as opposed to the heat capacity. Again, this data is not currently available, so we must use the best measures we can find today.

The process metrics are more difficult to determine, as simple measures are not readily available to characterize the environmental impact of processes. We want to relate the input to a process to the output. For example, we want to know for each widget that enters a process how much waste is generated or the quantity of airborne emissions. This type of data is not easy to find. Much of the needed data will come from suppliers. We will have to work closely with them, to gather the type of information we need. However, for sustainability we did find one metric where data was readily available: number of materials used in a process. This metric provides an indication of the sustainability of a process - the less materials a process uses the less impact it has on the environment. Obviously, this is a very simple metric and we need to focus on finding other metrics for processes.

In addition to the metric value, the uncertainty in the value is also captured to provide an indication of the data quality. The data quality is important, as it provides the user with an idea of how much uncertainty there is in a given value. In addition, it provides the developers of the tool an idea of which metrics need to be improved the most. This uncertainty value will be combined with the other metrics, to eventually provide an overall uncertainty value in the final impact score.

Step 4 - Scoring

The material and process metric scores are based on a scale of 0 to 100. This 0 to 100 scale allows several metrics to be combined to provide an overall impact e-score. For example at the metric level, a recycle rate of 75% for a particular material is converted to a score of 25 points, as a lower e-score is desired. The recycle efficiency value of 55% is converted to 45 points. The material recyclability score is the average of these two values, or 35 points per gram of material. This recyclability score is then averaged with other sustainability metrics to provide a material sustainability score. The impact scores are determined per gram of material, in order to weight the overall component score according to amount of the various materials. In the same way, process impact scores are determined per gram of input.

The overall sustainability score for a component is determined by a mass-weighted average for all the materials in a component. For example, if we have 4 g of material 1 (M1) and 2 gram of material 2 (M2) then the sustainability impact score is:

$$\text{Sustainability Score} = \frac{\text{mass(M1)*sustainability(M1) + mass(M2)* sustainability (M2)}}{\text{mass(M1) + mass(M2)}}$$

The uncertainty values for each metric will be propagated through to provide a final uncertainty value in the component. This propagation of error is important in order to understand the meaning of the final component e-score. We have included uncertainty values, where the information was available. However, as there was a very limited amount of data, we did not carry the error propagation through at this phase of tool development.

VI. DA Tool Applied to Shield Components

As global manufacturers of electronic equipment become more and more responsible for the environmental impact of their products, they must become proactive in understanding the choices they make when designing new products. It is for this reason, that in this paper we look at various shielding techniques and begin to examine the differences between shielding techniques from an environmental viewpoint, while remaining aware of other critical design parameters.

This section describes the application of the DA tool, using shield components as an example. First, a brief summary of shielding needs and options are described. Then, the results of the Design Scope for shield components are presented. Next, the metrics for the impact areas are applied to shields. Finally, three sample shields are scored and compared on the basis of their material impacts.

Introduction to Shielding

As the development of new electronic products has increased, so has the concern over electromagnetic interference within and from a product. Unwanted EMI can be generated by the circuitry within a product, and can also affect the product if the EMI is from an outside source. As electronic devices are both sources and receptors of EMI, this creates a two part problem. First of all, manufacturers must protect the operational performance of the device. Secondly, they must comply with regulations to minimize the electromagnetic radiation emitted to the atmosphere. These regulations and EMI problems within the product have given rise to a number of shielding techniques to shield electronic devices. These shielding techniques include various metal and plastic options. Plastic have begun to replace metals as they offer more design flexibility and reduced costs.

In general, they are several types of commercially available shields: metallic cans, coated plastic housings and conductive polymers. The coated plastic housings can be further grouped by the type of coating process: conductive fabric lamination, conductive foil application, electroplating, electroless plating(single and double sided), vacuum metallization, arc spraying, flame metallization and conductive paints. (See Exhibit 1)

Summary of EMI Shielding Design Considerations

When designing a shield there are several important factors that must be considered. First of all, a good shield is one where most of the electric and magnetic radiation is absorbed or reflected with minimal transmission. Shielding effectiveness, which is measured as attenuation in decibels, dB, is a common way measuring how well a shield functions. Of course, the shielding effectiveness of a material will vary depending on the surrounding circuitry and the frequency range it is in, therefore one can use data, such as that in Appendix A, only as a very "rough" guide. Attenuation levels in the range of 50Mhz to 2.5Ghz apply to modern communication and computer products. In general, the following guidelines apply for shielding effectiveness:

- 10-30dB minimal range of helpful shielding
- 30-90dB acceptable range of shielding
- 90-120dB excellent shielding
- 120dB and greater is state of the art

Secondly, corrosion resistance of the material is an important factor as this can effect the electrical conductivity and shielding effectiveness of the shield. Another critical factor for designers is cost. All of these factors must be balanced and traded off to complete the design of a shield. As the environmental factor becomes increasingly important this will be another factor that must be considered in the design process.

Design Scope for Shield Components

The results of the design scope for shield designs are shown as a flowchart in Figure 3. The information is organized to capture not only the various materials and processes used for shielding but it also captures the "design space". For example, the chart shows how a designer chooses first between metal and plastic, which then limits the manufacturing processes he or she can choose from. The process choice then leads to a limited list of material choices, and so on.

Understanding and capturing the design scope is an important part of this data collection effort as it helps the tool developer in organizing the information. The development of the flowchart provides a framework or capturing information. This helps considerably when interviewing designers, from many groups across Motorola, to understand the type of information needed for each component. The resulting flowchart provides us an idea of the number of materials and processes for a majority of the shield design options. This allows us to focus our metric investigation on a limited number of materials and processes. In addition, we realize that many of the material and processes used for shielding will also be used for other components. This will reduce our data collection efforts for other components.

Shield Material Metrics

Once the design scope for the shield components was completed, our next step was to determine the metric values for the materials and processes. We focused on metric values for materials, as process metric information is limited and this area of research will be the focus of the next phase of tool development. For energy use and toxicity, we determined values and scores for approximately 60% of the shield materials, as shown in Table 3 and 4. For sustainability, we were only able to determine values for recyclability, as shown in table 5. When a value could not be determined for a material then a score of 50 with an uncertainty range of 50 was given. In this way, a material choice was not penalized for lack of information. The other metrics: re-use, disassembly and remanufacturability are more complex and require further research and supplier specific information.

The data for recycle rate and recycle efficiency were calculated from data provided by the US Bureau of Mines and the American Plastics Council. We used this data as it was the best data available. Most of the data was from 1993, specific to the US, applied to all industries, and it was not necessarily limited to the electronics industry. However, we were able to generate approximate measures for the shield materials. The data is valid for this tool as long as we capture not only the uncertainty of the data but also document the source of data. This will be critical in the future, when we want to return and improve the data used in the tool.

Ideally, we prefer information from suppliers, but this is not usually possible. Generally, the recycle information we need is only available from our suppliers' suppliers. It is difficult enough today to get information from our own suppliers. This is an important issue in supply-chain management that need s to be addressed as we attempt to improve the quality of data in this tool.

Shield Scoring

After impact scores were determined for all possible shield materials, we applied the material scores to 3 sample shields to determine component e-scores. The shields represent a cross-section of shield components found across Motorola sectors. A description of each shield is given below:

Shield No.	Description
1	stamped cold-rolled steel with nickel eletroless-lating, reflowed on to board
2	die-casted zinc-aluminum with tin electroplating
3	injection-molded polycarbonate with copper and nickel electroless plating

The results for the overall shield e-scores are summarized below:

	Materials	Mass	Sustainability	Toxicity	Energy	Overall Score
Shield #1	cold-rolled steel	10	39	10	25.1	
	nickel (plating)	1	44.5	30	26.1	
impact score			39.5	11.8	25.2	**25.5**
Shield #2	zinc-aluminum	9	76.5	15		
	tin (plating)	2	68.5	20		
impact score			75.05	15.9	25.3	**38.8**
Shield #3	polycarbonate	15	90	20	50	
	copper (plating)	1	68.5	30	24.2	
	nickel (plating)	1	44.5	30	26.1	
impact score			84.4	16.7	45.9	**49**

The results indicate that shield #1 is preferred among the three shields. Shield #2 receives a higher score because it of toxicity from zinc and the poor recyclability of zinc-aluminum and tin. Shield #3 high score is a result of all three impact areas. The sustainability score is high because polycarbonate has a high recyclability score. The toxicity score is high because of the presence of both copper and nickel. Finally, the energy use for polycarbonate was not available, so it has a score of 50, which significantly raised the energy use score for shield #3. It is important not to focus on the score itself, but rather why the scores differ and if the difference merits a change in the design of the component. The scores are only to serve as guides to point the designer in the right direction, not to force them to choose between an e-score of 25 and 38.

Based on conventional wisdom, it makes sense that the metal shield would receive a lower score than a plastic shield, as the infrastructure is still developing for engineering plastics. Conventional wisdom cannot always be applied, as more metrics are developed and the parts that are designed are more complex. In addition, we have not taken into account the processes that are required to make these shields. A majority of the environmental impact could very well be from the processes rather than the materials. The learning from this study is that we must provide tools for designers so that they don't have to rely on conventional wisdom to guide them in environmentally conscious designs but rather on sound environmental rules of thumb.

A database tool is currently under development, to demonstrate how this tool will work in the designer's environment. The tool allows the designer to create a component and then evaluate the part based on a particular impact area. The tool also takes into account uncertainty and provides the user with an overall uncertainty value for the component based on the material and process selection. The tool also allows the user to combine components to create an assembly and receive an overall assembly e-score.

Exhibit 1

Shielding Alternatives

Metallic Cans

Metal shields are generally preferred when a high shielding effectiveness is needed , such as greater than 100dB due to their high conductivity's. The cans may be placed over individual components or a group of components. The metal shields are generally low cost as the part is usually simple and doesn't require any special features or complex designs. Metal cans are usually stamped using various metals such as cold-rolled steel, beryllium copper or nickel silver. The cans might also be die-cast using materials such as zinc or aluminum alloys.

Usually, these metal cans require plating to allow soldering to the printed circuit board which increases the cost of the part. There are some materials such as nickel silver that don't necessarily require plating. Generally, as designs become more complex and incorporate more features, metal cans become less attractive. In addition, the plating process that is used by suppliers generally tend to have environmental emissions and impacts that are quite undesirable.

Conductive Foils and Fabrics

Conductive foils for EM shielding only require the application of adhesive-backed foil. The foil can be applied to the inside of an injection-molded part. The foil is generally made of brass, aluminum, brass or a tin alloy.

Foils are generally used for prototyping as it is not economically feasible for mass production. Cutting and placing the foil is time-consuming and labor intensive.

Electroless Plating

Electroless plating is a method of depositing metal layers on a non-conductive material through a chemical reduction reaction (see table 2 for a list of raw materials required for the process). Each layer of metal is placed to act as a catalyst to continue the process, thereby building up the total metal thickness one layer at a time. Generally, shielding effectiveness in the neighborhood of 70 to 100 dB can be attained using this method.

The process involves a series of pretreatment baths in which the plastic part is etched and conditioned so that an electroless copper can be place. This is then overcoated with electroless nickel. The copper provides the shielding and the nickel provides corrosion resistance and in some cases helps with solderability.

Usually electroless plating is performed by subcontractor, as it requires very different needs than a plastic molding operation. Also the plating requires someone who can handle the waste effluent treatment and the large number of processing tanks needed.

Vacuum Metallization

The process of vacuum metallization is one in which a metal source is heated enough so that it vaporizes in an evacuated enclosure which contains the component to be metallized. The metal atoms then condense onto the component.

There are wide variety of coatings that can be applied, including aluminum and gold. A shielding effectiveness of 50 to 90 dB can be attained.

Arc Spraying

This process usually involves the use of zinc metal wires which are fed through an electric arc which melts the metal. Compressed air is then used to atomize the molten metal and propel the droplets onto the target component where they spread out and solidify into a dense layer. The spraying equipment is similar to that of a spray gun and deposits the metal in a similar manner.

The zinc metal usually provides SE in the 30 to 80 dB range (which is higher than nickel-based paints). But this method is undesirable from an environmental standpoint due to the toxicity of the zinc metal vapor. [13]

Conductive Paints

The use of organic coatings combined with copper, silver or nickel filler is a common approach to shielding plastic moldings. The paint can be applied with spray painting equipment.

The selection of filler material determines the shielding effectiveness and cost of the paint. Silver filler tends to give the highest SE of up to 85 dB but it is also the most expensive. Copper also gives good results but is prone to oxidation when exposed to an industrial atmosphere. Therefore, nickel is the most commonly used filler providing SE in range of 30 to 60 dB.[14]

Paints can be easily applied through a manual operation and on large production runs through the use of robots. The paint can also be applied by masking certain areas to leave some areas coated and other areas uncoated.

Some of the problems associated with paints, besides the low shielding levels, are the control of applying a uniform coating to the entire part. In addition, from an environmental standpoint the paints are generally solvent based which is not preferred due to the volatile organic compounds associated with solvent system. But, there has been the recent development of water based paints which are being tested and used in some applications.

Conductive Polymers

Conductive polymers are made from the incorporation of conductive fibers into the polymers. The fibers are generally graphite with electroplated nickel coatings. The fibers are usually mixed into the polymer before the injection molding process through dry blend mixing. Right now this process is still under investigation, as high levels of shielding effectiveness have not yet been achieved with this material.

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[13] Brown, B.E., Hill J. T., Archibald, L.C., "RFI/EMI shielding of plastic enclosures", Eighth International Conference on Electromagnetic Compatibility, London, UK, 1992.
[14] Ibid.

APPENDIX A

EMI Shielding Effects of Various Methods[15]

Method	Shielding Capability	Comments
Stamped Metal Cans	> 100 dB	Depends on material thickness.
Conductive Fabrics	~50 dB	
Electroless Plating (copper/nickel)	70-100 dB	
Al Vacuum Metallization	40 - 70 dB	Coating about 2.3 - 5μm thick
Zinc Arc Spraying	60 - 90 dB	Coating about 70μm thick
Conductive Paints	~20 dB	with silver paints up to 85 dB
Conductive Composites w/graphite filler	20-30 dB	
Conductive Composites w/ metal coated fillers	40-60 dB	Copper fibers, aluminum flakes etc. applied as fiber

[15] Table adapted from, "Technical Progress of EMI Shielding Materials in Japan" by Sachio Yasufuku, IEEE Electrical Insulation Magazine, Vol. 6 No.6, p. 29, November/December 1990.

TABLE 1

Sustainability (Recyclability)								
	Recycle Rate			Recycle Efficiency			Overall Score	
Material Name	Value[16]	Uncer-tainty[17]	Score[18]	Value[1]	Uncer-tainty[2]	Score[3]	Score[19]	Uncer-tainty[20]
Nickel	16	2.4	84	95	14.25	5	44.5	14.45
Aluminum Sheet	25	3.75	75	36	5.4	64	69.5	6.57
Iron & Steel	27	4.05	73	95	14.25	5	39	14.81
Copper	22	3.3	78	30	4.5	70	74	5.58
Tin	16	2.4	84	47	7.05	53	68.5	7.45
Zinc	12	1.8	88	21	3.15	79	83.5	3.63
Polycarbonate[a]	10	5	90	10	5	90	90	7.07
ABS[a]	10	5	90	10	5	90	90	7.07
zinc-aluminum alloy[b]	18.5	2.775	81.5	28.5	4.275	71.5	76.5	5.10

[16] Recycle Rate as defined by U.S. Bureau of Mines is post-consumer scrap consumption divided by apparent consumption. Recycle Efficiency defined as post-consumer scrap divided by (post-consumer scrap generated plus net imports, or minus net exports). Figures for chromium, molybdenum, and tantalum are based on total scrap consumption. Source of data: Sibley, Scott and Butterman, William, "Metals Recycling in U.S.", *Draft*, US Bureau of Mines 1993.

[17] Estimated range of uncertainty for recycle data as it applies to electronics industry. Range of plus or minus 15% determined by interviews with several experts in metal and plastic materials from U. S. Bureau of Mines and American Plastics Council. Uncertainty is 15% of recycle value

[18] Score based on scale of 0 to 100, 0 being the most desirable score of 100%.
Score = -Value*10+100, maximum score is 100

[19] Average Score of recycle rate and recycle efficiency values. Assumed that both values contribute equally to recyclability metric.

[20] Determined by assuming uncertainty in recycle rate and recycle efficiency represent an estimated sigma of 67% confidence.
overall uncertainty=sqrt (sigma^2 (recycle rate) +sigma^2 (recycle efficiency))

[a] Currently polycarbonate and ABS recycling data are not collected because recycling of these plastics is very limited. Plastics data estimated by American Plastics Council material experts based on U.S. Bureau of Mines definition of recycle rate.

[b] Zinc-aluminum alloy defined as consisting of 50% zinc and 50% aluminum. Values for zinc and aluminum are averaged to determine a value of zinc-aluminum. 50/50 assumption used when alloy number is unspecified.

TABLE 2

TOXICITY[21]				
Material Name	HMIS - Fire	HMIS - Health	HMIS - Reactivity	E-Score[22]
Nickel (Plating)	0	3	0	30
Aluminum Sheet				
Iron & Steel (cold-rolled steel)	0	1	0	10
Copper (Copper Alloys)	0	3	0	30
Tin (electrolyte plate)	0	2	0	20
Zinc (castings)	1	1	0	20
Polycarbonate	1	1	0	20
ABS				
zinc-aluminum alloy				15

[21] Toxicity scores based on HMIS values, these values are from a database developed for the exclusive use of Motorola. The basis for the scores are the MSDS sheets.
[22] Score is based on the individual scores for reactivity, fire and health. Each individual score is multiplied by 10 then summed for a total e-score. The range of possible toxicity scores is therefore 10 to 90.

TABLE 3

ENERGY USE	
Material Name	Score[23]
Nickel	26.1
Aluminum Sheet	24.4
Iron & Steel	25.1
Copper	24.4
Tin	27.11
Zinc	25.4
Polycarbonate[a]	50
ABS[a]	50
zinc-aluminum alloy	24.9

[23] Score is based on heat capacity (J/mol K) of the material. The heat capacity is normalized to a value of 100.
a Values for polycarbonate and ABS can not be determined, so they are given median values of 50.

TABLE 4

Process - Material Diversity[24]						
Process Name	**Lower Limit[25]**	**Upper Limit**	**Lower Score[26]**	**High Score**	**Score[27]**	**Score Range[28]**
stamping	2	2	20	20	20	0
die-casting	2	4	20	40	30	10
extrusion			0	100	50	50
injection-molding	2	4	20	40	30	10
electroplating (1 matl)	5	9	50	90	70	20
conductive fabric lamination			0	100	50	50
electroless plating for plastic (1 matl)	14	17	100	100	100	0
electroless plating for metals (1 matl)	7	10	70	100	85	15
electroless plating for plastics (2 matl)	18	21	100	100	100	0
vacuum metallization	2	4	20	40	30	10
conductive paints	1	3	10	30	20	10
gasketing			0	100	50	50
reflow			0	100	50	50
wave solder			0	100	50	50

[24] Defined as number of materials used in a particular process. This includes the use of the primary material, lubricants, cleaning chemcials etc.
[25] Based on minimal number of chemicals/materials required for the process.
[26] A process with 1 material recevies a 10, 2 receives a 20 etc. Any process with more than 10 materials gets a score of 100.
[27] Based on average of high and low score.
[28] Difference between high and low score.

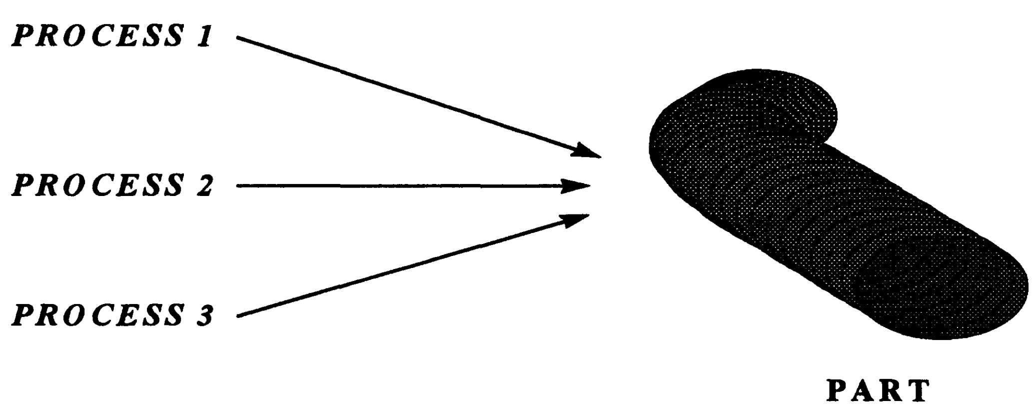
Appendix III

Description of DfE Tool Demonstration Accounting System

One of the main purposes of the DfE tool demonstration developed for Motorola and UTC was to demonstrate how an accounting system can help a company track the environmental impact of its products through user defined metrics. The accounting system separates a product into its fundamental parts and processes. The fundamentals of the accounting system are described below.

Assembly - An assembly is a combination of one or more parts. It is created based on the number of parts that are defined in the database. An example of an assembly is an engine controller which is made up of many different parts such as, circuit boards, EMI shields, screws, nuts etc.

Part - A part is defined by the processes needed to create the part (as shown below).



Again, the processes are selected from the existing database. Along with the selection of a process, the amount of process used and the uncertainty factor are also tracked. The amount corresponds to the amount of process needed to create one unit of the part. The uncertainty factor refers to a 95% confidence range in the amount of process entered. For example, if 1 unit of a plastic EMI shield part is created from 0.9 to 1.1 units of polycarbonate production then an amount of 1 with an uncertainty factor of 0.1 is recorded. The uncertainty factor is then propagated through to the final assembly to provide an overall uncertainty measure of the environmental impact of the assembly.

Process - A process is defined by its inputs and outputs (as shown in the below).

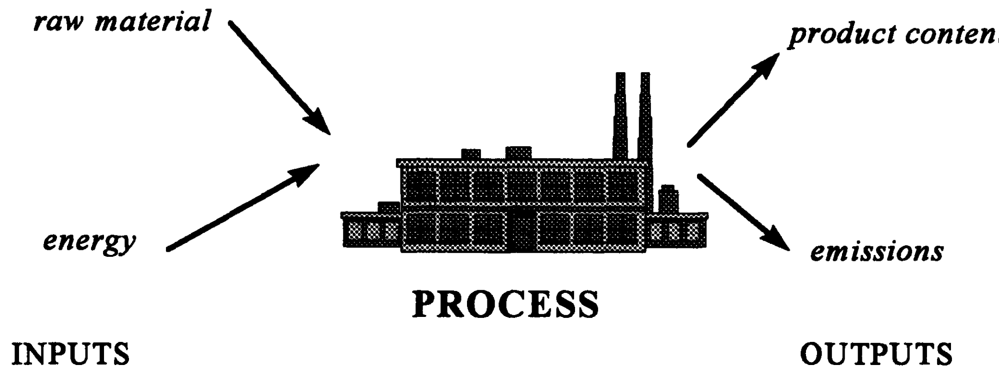


Figure 1: Definition of a Process

In order to define a process an input or output is entered (from the database) and an amount and uncertainty factor is entered (as described previously). For example, a nickel electroplating process has a product content output of Nickel Content and an emission of Waterborne Nickel (among others). Each of these also has amounts that correspond to 1 unit of Nickel Electroplating and an uncertainty factor. Obviously, the more information known about a processes' inputs and outputs results in an improved process model.

The purpose of breaking down an assembly into its fundamental parts and processes is to provide an easy way to measure the environmental impact. For example, a metric might be defined as the heavy metal content within an assembly. The heavy metal content is defined as the amount of lead and cadmium used to create a particular assembly or part. The accounting system then searches all the processes that make up the part (or assembly) and provides a total heavy metal content amount along with an uncertainty factor to indicate the "quality" of the information within the database.