

CHAPTER 1

DESIGN FOR ENVIRONMENT (DfE): STRATEGIES, PRACTICES, GUIDELINES, METHODS, AND TOOLS

Daniel P. Fitzgerald

Department of Mechanical Engineering and Institute for Systems Research University
of Maryland, College Park

Jeffrey W. Herrmann

Department of Mechanical Engineering and Institute for Systems Research University
of Maryland, College Park

Peter A. Sandborn

Department of Mechanical Engineering and Institute for Systems Research University
of Maryland, College Park

Linda C. Schmidt

Department of Mechanical Engineering and Institute for Systems Research University
of Maryland, College Park

Thornton H. Gogoll

Director, Engineering Standards Black & Decker Inc. Towson, Maryland

1 INTRODUCTION	2	3.4 Detailed Design Environmental Review	14
1.1 Design for Environment	2	3.5 Final Environmental Review	14
1.2 Decision Making in New Product Development	3	3.6 Postlaunch Review	14
1.3 Environmental Objectives	4	3.7 Feedback Loop	15
2 CREATING A DESIGN FOR ENVIRONMENT PROGRAM	5	4 USING DfE TOOLS	15
2.1 Identifying and Understanding the Stakeholders	5	4.1 Guidelines and Checklist Document	15
2.2 Creating Environmental Objectives	6	4.2 Product Design Matrix	16
2.3 Metric Selection	8	4.3 Environmental Effect Analysis	16
2.4 Incorporating DfE into the Design Process	10	4.4 Life-cycle Assessment	19
2.5 Fitting All the Pieces Together	11	5 EXAMPLES OF DfE INNOVATIONS	19
3 IMPLEMENTING A DfE PROCESS	12	5.1 Forever Flashlight	19
3.1 Product Initiation Document	12	5.2 Battery-Free Remote Control	20
3.2 Initial Environmental Review	13	5.3 Toshiba's GR-NF415GX Refrigerator	20
3.3 Conceptual Design Environmental Review	14	5.4 Matsushita Alkaline Ion Water Purifier	21
		6 CONCLUSIONS	21

2 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

1 INTRODUCTION

Throughout their life cycle, products generate environmental impacts (1) from extracting and processing raw materials; (2) during manufacturing, assembly, and distribution; (3) due to their packaging, use, and maintenance; and (4) at their end of their life. Environmentally benign products are products that comply with environmental regulations and may have significant features that reduce environmental impact. The ideal environmentally benign product is one that not only would be environmentally neutral to make and use but also would actually reverse whatever substandard conditions exist in its use environment. The ideal environmentally benign product would also end its life cycle by becoming a useful input for another product instead of creating waste.

In the past, manufacturing firms were concerned with meeting regulations that limited or prohibited the pollution and waste that are generated by manufacturing processes. However, regulations are now focusing on the material content of the products that are sold in an effort to control the substances that enter the waste stream.

There are many ways to minimize a product's environmental impacts. Clearly, however, the greatest opportunity occurs during the product design phases, as discussed by many authors, including Handfield et al., Fiksel, Bras, and Ashley.¹⁻⁴ Therefore, organizations that develop new products need to consider many factors related to the environmental impact of their products, including government regulations, consumer preferences, and corporate environmental objectives. Although this requires more effort than treating emissions and hazardous waste, it not only protects the environment but also reduces life-cycle costs by decreasing energy use, reducing raw material requirements, and avoiding pollution control.⁵

Design for Environment (DfE) tools, methods, and strategies have therefore become an important set of activities for product development organizations.

1.1 Design for Environment

Design for Environment (DfE) is “the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle.”² DfE, like other concurrent engineering techniques, seeks to address product life-cycle concerns early in the design phase. Thus, it is similar to design for manufacturing (DFM), design for assembly (DFA), and design for production (DFP).⁶ DfE combines several design-related topics: disassembly, recovery, recycling, disposal, regulatory compliance, human health and safety impact, and hazardous material minimization.

Some designers view DfE as simply calculating an environmental measurement, similar to estimating cost. This perception is due to the trend of companies implementing standalone DfE tools without explanation. As Lindahl states, “When the designers and actual users of the methods do not understand the reason why, or experience any benefits from using the DfE methods, there is a risk that

they utilize the methods but do not use the results, or that they run through the method as quickly as possible.”⁷ Therefore, designers produce an environmental output and consider the environmental work finished. A more effective approach is to design and implement a sound DfE process, as this chapter explains.

1.2 Decision Making in New Product Development

Decision making is an important activity in new product development, and a great variety of decisions need to be made. Generally speaking, these fall into two types: design decisions and management decisions.

Design Decisions

Design decisions address the question, “What should the design be?” They determine shape, size, material, process, and components. These generate information about the product design itself and the requirements that it must satisfy.

Management Decisions

Management decisions address the issues of what should be done to make the design into a successful product. Management decisions control the progress of the design process. They affect the resources, time, and technologies available to perform development activities. They define which activities should happen, their sequence, and who should perform them. That is, what will be done, when will it be done, and who will do it. The clearest example is project management: planning, scheduling, task assignment, and purchasing.

In studying design projects, Krishnan and Ulrich provide an excellent review of the decision making in new product development, organized around topics that follow the typical decomposition of product development.⁸ Herrmann and Schmidt describe the decision-making view of new product development in more detail.^{9,10} Traditionally, factors such as product performance and product cost have dominated design decisions, while time to market and development cost have influenced management decisions. Of course, many decisions involve combinations of these objectives.

Considering environmental issues during decision making in new product development, while certainly more important than ever before, has been less successful for manufacturers than considering other objectives. Environmental objectives are not similar to the traditional objectives of product performance, unit cost, time to market, and development cost. All four objectives directly affect profitability and are closely monitored. Unit cost, time to market, and development cost each use a single metric that is well understood and uncomplicated. Although product performance may have multiple dimensions, these characteristics are quantifiable and clearly linked to the product design. Designers understand how changing the product design affects the product performance. Environmental objectives do not have these qualities.

4 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

1.3 Environmental Objectives

Under pressure from various stakeholders to consider environmental issues when developing new products, manufacturing firms have declared their commitment to environmentally responsible product development and have identified six relevant goals:

1. *Comply with legislation.* Products that do not comply with a nation's environmental regulations cannot be sold in that nation.
2. *Avoid liability.* Environmental damage caused by a product represents a financial liability.
3. *Satisfy customer demand.* Some consumers demand environmentally responsible products. Retailers, in turn, pass along these requirements to manufacturers.
4. *Participate in eco-labeling programs.* Products that meet requirements for eco-labeling are more marketable.
5. *Enhance profitability.* Certain environmentally friendly choices such as remanufacturing, recycling, and reducing material use make good business sense and have financial benefits.
6. *Behave ethically.* Being a good steward of the planet's resources by considering the environment during the product development process is the right thing to do.

Despite the high profile given to these objectives at the corporate level, product development teams assign a *back-burner* status to environmental issues. Environmental *objectives*, for the most part, are driven by regulations and social responsibility, and reducing environmental impact doesn't clearly increase profit. Product managers are not often willing to compromise profit, product quality, or time to market in order to create products that are more environmentally benign than required by regulations. (The exceptions are those organizations that court environmentally conscious consumers.)

Environmental *performance*, however, is measured using multiple metrics, some of which are qualitative. Moreover, these metrics may seem irrelevant to the firm's financial objectives. Measuring environmental performance, especially life-cycle analysis (LCA), can require a great deal of effort.

With environmental performance it is harder to make trade-offs. It is not clear how to select between design alternatives because there is no aggregate measure to calculate. One designer presents an excellent example:

You have two ways of building a part. One option is based on metal. Metal is heavy (thus, it consumes more resources). It also creates waste during the actual manufacturing process (in form of sludge). However, it can be recycled when it reaches the end of its product life. In contrast, we make the product out of graphite. This part is lighter (which means it consumes less energy in use). In addition, it can be molded rather than machined (again resulting in less waste). However, when it

reaches the end of its life, it must be disposed of in a landfill since it cannot be recycled. Which of these two options results in a greener product?¹

2 CREATING A DESIGN FOR ENVIRONMENT PROGRAM

This section describes the step necessary for creating a DfE program within a product development organization.

2.1 Identifying and Understanding the Stakeholders

The first step in creating a DfE program is to identify and understand the environmental stakeholders. A *stakeholder* is defined in the *American Heritage Dictionary* as one who has a share or an interest, as in an enterprise.¹¹ Stakeholders ultimately define the objectives and resulting environmental metrics of the DfE program. The following are examples of typical stakeholders for product development organizations:

- *Board members.* Internal stakeholders on the board of directors directly define corporate policies and culture.
- *Socially responsible investors.* These stakeholders invest in companies that demonstrate socially responsible values such as environmental protection and safe working conditions.
- *Non-government organizations.* Organizations such as the Global Reporting Initiative Work to advance specific environmental agendas.
- *Government organizations.* Organizations such as the EPA require meeting certain environmental regulations and provide incentives such as the Energy Star for achieving an exceptional level of environmental compliance.
- *Customers.* A customer is anyone who purchases the firm's product down the line. This could be a retailer, another product development organization, or an end user.
- *Competitors.* Competitors are other product development organizations that are in the same market. It is important to benchmark competitors to understand the environmental issues and strategies within the firm's market and to effectively position the organization in the market.
- *Community.* The community consists of people affected by the organization's products throughout their life cycle. Depending on the scope of the assessment, this can technically be everyone in the world. More realistically, it is the community that surrounds the organization's facilities and directly interacts with the products.

Each stakeholder has different environmental interests, which leaves the organization with a considerable amount of environmental demands to meet. Since

6 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

product development organizations operate with limited resources, the stakeholders will need to be prioritized based on their influence on the organization. Influence generally correlates to the extent that profits will be affected if a stakeholder's demand is not met. Once the stakeholders are prioritized, the product development organization will have a good idea of which environmental demands need to be met. It is now possible to construct a DfE program with objectives and metrics that support these demands.

2.2 Creating Environmental Objectives

After a thorough analysis of the stakeholders, it is possible to create environmental objectives for the DfE program. The environmental objectives will need to align with as many of the environmental demands of the stakeholders as possible. The objectives will also need to align with the values and culture of the corporation. Klein and Sorra argue that successfully implementing an innovation (in this case, a DfE program) depends on “the extent to which targeted users perceive that use of the innovation will foster the fulfillment of their values.”¹² Since it is necessary for an employee to adapt to the values of the corporation to be successful, a DfE program that aligns to corporate values will align with employee values and should be successfully implemented. When creating environmental objectives, it is important to use the correct level of specificity. The objectives should be broad enough that they do not have to be frequently updated but specific enough that they provide consistent direction for the DfE program. An environmental objective of “protect the Earth” would be too broad, while “eliminate the use of lead” would be too specific. Environmental objectives should have lower-level targets associated with them so the company can assess its progress toward objectives. For example “eliminate the use of lead” could be a lower-level target for the environmental objective “reduce the use of hazardous materials.”

For example, Black & Decker created environmental objectives for its DfE process.¹³ Its DfE process contains values that coincide with the organization's values. Within the Corporation's Code of Ethics and Standards of Conduct, there is a section titled Environmental Matters. It “places responsibility on every business unit for compliance with applicable laws of the country in which it is located, and . . . expects all of its employees to abide by established environmental policies and procedures.”¹⁴ The objectives also meet the environmental demands of stakeholders as described next.

Practicing Environmental Stewardship

Black & Decker seeks to demonstrate environmental awareness through creating an environmental policy and publishing it on its Web site, including information about recycled content on packaging and its design for environment program. In addition, Black & Decker belongs to environmental organizations such as

the World Environmental Center, which contributes to sustainable development worldwide by strengthening industrial and urban environment, health, and safety policies and practices. It is also member of the Rechargeable Battery Recycling Corporation (RBRC) and RECHARGE, which both promote the recycling of rechargeable batteries.

Complying with Environmental Regulations

As a global corporation that manufactures, purchases, and sells goods, Black & Decker must comply with all applicable regulations of countries where its products are manufactured or sold. Currently, the European Union exerts significant influence on addressing environmental issues through regulations and directives. This section lists some important U.S. and European environmental regulations.

Many U.S. regulations apply to U.S. and European workers, and these are set by both federal and state agencies. The Occupational Safety & Health Administration (OSHA) limits the concentration of certain chemicals to which workers may be exposed. The Environmental Protection Agency (EPA) regulates management of waste and emissions to the environment. Black & Decker provides employees with training on handling hazardous wastes, which is required by the Resource Conservation and Recovery Act and the Hazardous Materials Transportation Act. California's Proposition 65 requires a warning before potentially exposing a consumer to chemicals known to the State of California to cause cancer or reproductive toxicity. The legislation explicitly lists chemicals known to cause cancer and reproductive toxicity.

The European Union also regulates corporations with respect to environmental issues. The EU Battery Directive (91/157/EEC) places restrictions on the use of certain batteries. The EU Packaging Directive (Directive 2004/12/EC)¹⁵ seeks to prevent packaging waste by requiring packaging reuse and recycling. In the future, countries in the European Union will require Black & Decker to adhere to certain laws so that the state achieves the goals of the EU Packaging Directive. Thus, Black & Decker will be interested in increasing the recyclability of its packaging. The new EU directives on waste electrical and electronic equipment (WEEE) and on the restriction of the use of certain hazardous substances in electrical and electronic components (RoHS) address issues of product take-back and bans on hazardous materials, respectively. Thus, Black & Decker must provide information about the material content of its products.

Addressing Customer Concerns

Black & Decker's retail customers are concerned about the environmental impacts of the products they sell. Examples of customer concerns are ensuring timber comes from appropriate forests; increasing the recyclability and recycled content in packaging; using cadmium in batteries; and using lead in printed wiring boards and electrical cords. More specifically, some retailers require that Black & Decker's products be free of lead-based surface coatings.

8 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

Mitigating Environmental Risks

An activity's environmental risk is the potential that the activity will adversely affect living organisms through its effluents, emissions, wastes, accidental chemical releases, energy use, and resource consumption.¹⁶ Black & Decker seeks to mitigate environmental risks through monitoring chemical emissions from manufacturing plants; reducing waste produced by its operations; ensuring safe use of chemicals in the workplace; and ensuring proper off-site waste management.

Reducing Financial Liability

There are different types of environmental liabilities:¹⁷

- Compliance obligations are the costs of coming into compliance with laws and regulations.
- Remediation obligations are the costs of cleaning up pollution posing a risk to human health and the environment.
- Fines and penalties are the costs of being noncompliant.
- Compensation obligations are the costs of compensating damages suffered by individuals, their property, and businesses due to use or release of toxic substances or other pollutants.
- Punitive damages are the costs of environmental negligence.
- Natural resource damages are the costs of compensating damages to federal, state, local, foreign, or tribal land.

Not all of these environmental liabilities apply to all firms.

Reporting Environmental Performance

Black & Decker reports environmental performance to many different organizations with local, national, or global influence and authority. An example of such an organization is the Investor Responsibility Research Center (IRRC).

2.3 Metric Selection

After the environmental objectives are set, an organization needs environmental metrics to measure its progress. Many aspects need to be considered when selecting metrics for a DfE program. First, each metric should directly relate to at least one of the environmental objectives. Metrics that relate to many objectives tend to be more desirable. Second, the organization has to have the capability of measuring the metric. A metric that can be easily measured within an organization's systems ranks higher than a metric that requires costly changes and upgrades. Finally, the metrics should tailor to specific stakeholder reporting requests. An analysis of the most asked for metrics can help prioritize the metrics. Since organizations operate with limited resources, the metrics will need to be prioritized based on these aspects. It should be noted that while most metrics are quantitative, qualitative metrics such as an innovation statement do exist.

The following section briefly describes eight product-level environmental metrics developed by the authors and Black & Decker staff that product development teams can evaluate during the product development process.

Flagged Material Use in Product

This metric measures the mass of each flagged material contained in the product. A material is considered *flagged* if it is banned, restricted, or being watched with respect to regulations or customers. A consulting firm has provided Black & Decker with a list of materials that are banned, restricted, and being watched.

Total Product/Packaging Mass

This metric measures the mass of the product and packaging separately.

Flagged Material Generated in Manufacturing Process

This is a list of each flagged material generated during the manufacturing process. A material is considered flagged if it is banned, restricted, or being watched with respect to regulations or customers.

Recyclability/Disassembly Rating

This metric is the degree to which each component and subassembly in the product is recyclable. Recyclability and separability ratings can be calculated for each component based on qualitative rankings. Design engineers are provided with a list of statements that describe the degree to which a component is recyclable or separable, and a value from 1 to 6 is associated with each statement. Low ratings for both recyclability and separability facilitate disassembly and recycling. The design engineer rates the recyclability and separability of each component, subassembly, and final assembly. If both ratings for an item are less than 3, then the item is recyclable.¹⁸

Disassembly Time

Disassembly time is a measure of the time it will take to disassemble the product. Research has been conducted on how long it typically takes to perform certain actions. Charts with estimates for typical disassembly actions are provided to the design engineers, who can then estimate how long it would take to disassemble a product.¹⁸

Energy Consumption

The total expected energy usage of a product during its lifetime. This metric can be calculated by multiplying the total expected lifetime hours by the energy use per hour the product consumes. This metric needs to be calculated only for large energy consumers such as compressors, generators, and battery chargers.

10 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

Innovation Statement

A brief paragraph describes the ways a product development team reduced the negative environmental impact of their product. The product development team should write this after the product is launched. All environmental aspects considered should be included as well.

Application of DfE Approach

This binary measure (yes or no) is the answer to the following question: Did the product development team follow the DfE approach during the product development process? Following the DfE approach requires the team to review the DfE guidelines and evaluate the product-level environmental metrics. Although this list of metrics cannot completely measure every environmental impact, the metrics provide designers with a simple way to compare different designs on an environmental level. Black & Decker plans to track the trends of these metrics as the products advance through future redesigns. Furthermore, each product will have environmental targets set at the beginning of the project, and the metrics provide a way to track how well the product development team performed with respect to attaining the targets. The Corporate Environmental Affairs group will also use the metrics to respond to retailers' requests for environmental information.

2.4 Incorporating DfE into the Design Process

Incorporating a DfE process that fits into the existing product development process has significant potential to help manufacturing firms achieve their environmental objectives. By researching the organization's product development process and understanding the decision-making processes, information flow, and organizational and group values, it is possible to construct a DfE process that is customized and easy to implement. The product development process needs to be studied to ensure information availability for the desired metrics. Ideally, the DfE process should leverage existing processes in order to minimize time to market and require little extra effort from the designers.

The safety review process is an example of an existing process that most product development organizations have that can be combined with the DfE process. Most product development organizations implement a formal safety review process to ensure that the final product is safe for consumer use.^{19,20} Typically, safety reviews are held at predetermined key points in the product development process. During these reviews, members from the design team and other safety specialists, such as liability and compliance representatives, meet to discuss the current product design. The meetings are run in a brainstorming format and can be guided by a checklist or company-specific agenda. One safety specialist is in charge of final decisions concerning safety. Since product safety includes qualitative measures, it is necessary to assess the issue in a meeting format where ideas and issues can be discussed with all interested parties.

There are major similarities between safety and environmental concerns. Both areas are important but are not closely linked to profitability (as are quality, cost, and time to market). Both areas involve subjective assessments on a variety of factors, many of which are qualitative. This suggests that most product-development organizations should treat environmental objectives in the same way that they treat safety concerns. It is necessary to assess a product's environmental performance at key stages in the product-development process. Furthermore, since assessing environmental performance requires information from multiple business units within the product-development organization, the organization will need to hold a meeting to discuss the issues with all interested parties. By expanding the safety review process, organizations that have similar corporate objectives for safety and for environmental issues can create a practical DfE process that should be simple to implement.

Manufacturing firms with elaborate safety evaluation and verification procedures (used in areas such as aircraft manufacturing) may not require a similarly sophisticated DfE process (unless the product has many environmental concerns, as in automobile manufacturing). However, in firms that don't explicitly consider safety during new product development, establishing a DfE process will be more work, but the need for a DfE process remains.

The safety and environmental objectives of product-development organizations vary considerably from firm to firm, and each firm uses different mechanisms for addressing these concerns. Certainly, practices that make sense in one domain may be impractical in another. This approach is based on the similarity of the safety objectives and environmental objectives. In firms where the safety objectives and environmental objectives are quite different in scope, other types of DfE processes will be more effective.

2.5 Fitting All the Pieces Together

A DfE program cannot be implemented in isolation from other programs within a product-development organization. The program needs to be integrated with other programs that fall under the corporate responsibility umbrella and carry the same weight. Typical corporate responsibility programs include giving back to the community, promoting diversity awareness, ensuring proper working conditions and benefits for employees, and environmental awareness. These programs have detailed plans and goals that are disseminated to all employees through a substantial medium such as a communications meeting. The employees then begin "living" these programs, which results in a corporate culture.

Most product-development organizations' environmental awareness initiatives are based at the manufacturing level rather than the product level. A new DfE program will most likely be integrated with this preexisting portion of environmental awareness. Upon implementation, the program objectives and specific process need to be clearly presented to employees. The commitment from the

12 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

upper management within the organization should be enough to get the program rolling. If there is resistance, the organization may need to implement a system that rewards those who participate (and has consequences for those who don't). Only after seeing the organization's commitment and receiving direction can the engineers do their jobs and determine how to meet the goals.

3 IMPLEMENTING A DfE PROCESS

This section describes a new design for environment process that will be implemented at Black & Decker.¹³ The company defined a DfE process that naturally integrates environmental issues into the existing product-development process with little extra effort or time. Black & Decker uses a *stage-gate* product-development process that has eight *stages*. Every stage requires certain tasks to be completed before management signs off, giving permission to proceed to the next stage. This sign-off procedure is known as the *gate*.

Currently, Black & Decker has safety reviews during stages 2, 3, 4, and 6. Safety reviews are meetings intended for reviewers to evaluate the assessment, actions, and process of the design team in addressing product safety. The DfE process adds an environmental review to the agenda of the safety reviews held during stages 2, 4, and 6. A separate environmental review will be held during stage 3, an important design stage, in order to focus specifically on the environmental issues for the particular product. The environmental reviews will require design teams to review the checklist of key requirements and to consider guidelines for reducing environmental impact. When the DfE process is first implemented, design teams will have to fill out the environmental scorecard only during stage 6 after the product design is complete. Doing this begins the process of recording environmental data and allows design teams to adapt gradually to the new process. When design teams become more familiar with the process, the scorecard will be completed two or more times during the stage-gate process in order to track design changes that affect environmental metrics during the development process.

Environmental targets will be set during stage 1 as goals for the new product. The design team will write a lessons-learned summary during stage 8 to highlight innovative environmental design changes. The lessons-learned summary will provide the innovation statement metric. Figure 1 shows the Safety Review Process and Environmental Review Process running in parallel. The following sections discuss the aforementioned environmental activities in more detail. Note that, throughout this process, many other product-development activities are occurring, causing changes to the product design.

3.1 Product Initiation Document

The product initiation document is a document that Black & Decker uses to benchmark competitors, define performance targets, and predict profitability and

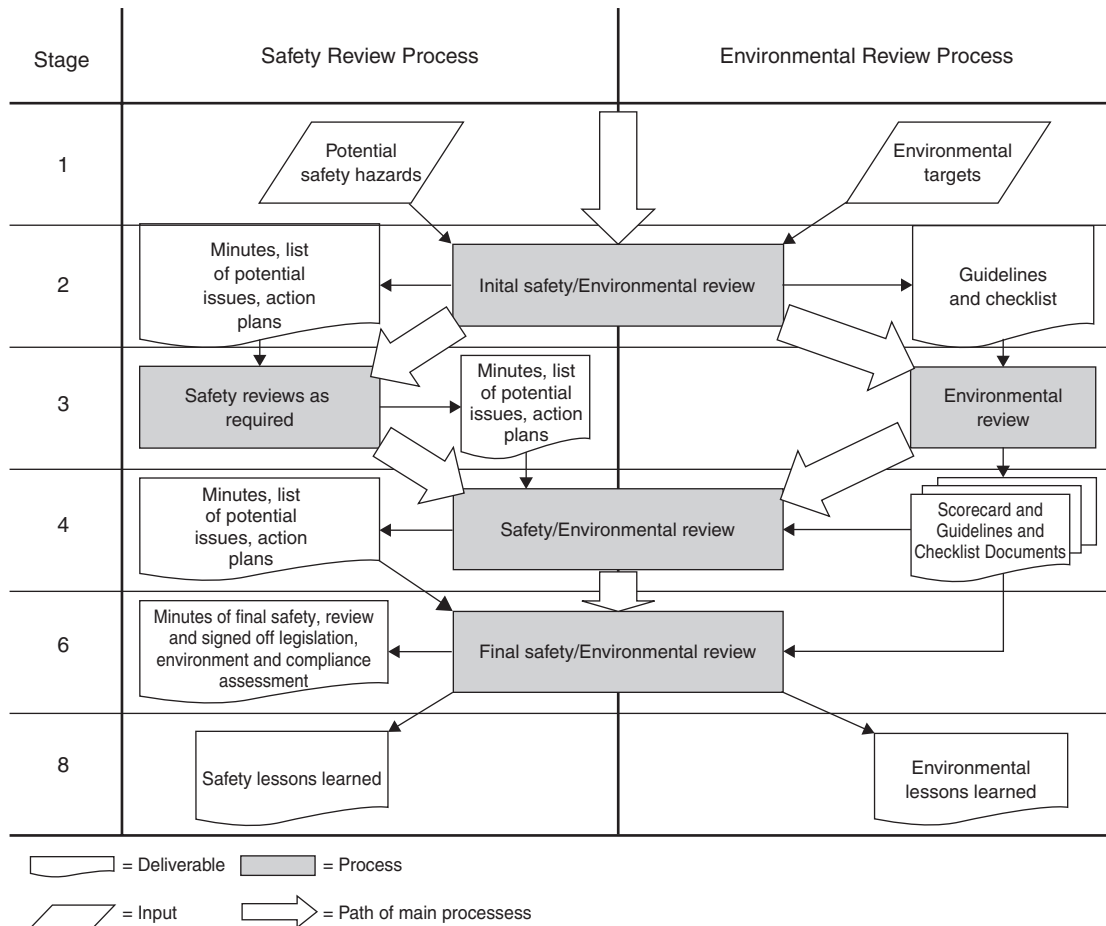


Figure 1 Combined safety and environmental review process.

market share. In addition to these issues, the product initiation document will also address environmental regulations and trends and opportunities to create environmental advantage. Targets for environmental improvement will also be included.

3.2 Initial Environmental Review

The first environmental review is coupled with a safety review. During this meeting, the design team should discuss current environmental regulations, design guidelines, and environmental metrics. A list of regulations and design guidelines can be found in the guidelines and checklist document. The environmental metrics are located in the environmental scorecard. Old lessons learned documents from similar products will be reviewed during this meeting to facilitate

14 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

environmental design ideas. The result of the meeting is an initial assessment plan that includes the tests to be conducted and the analysis to be performed. The reliability representative will write the assessment plan. Also, a list of brainstormed ideas for environmental improvement and any other minutes will be included in the assessment plan.

3.3 Conceptual Design Environmental Review

The second environmental review is held separately from the safety hazard review. During this meeting, the project team will check compliance regulations, fill in the guidelines and checklist document, discuss the metrics in the scorecard, and review opportunities and additional environmental issues. The result of this meeting is an updated guidelines and checklist document and meeting minutes. The reliability representative will update the guidelines and checklist document and write the minutes. The lead engineer will update the scorecard for the next meeting.

3.4 Detailed Design Environmental Review

The third environmental review is coupled with a safety review. During this meeting, the project team should ensure that all environmental compliance issues are resolved. There should be no further changes to the design due to environmental reasons after this meeting. The result of the meeting is an updated guidelines and checklist document and meeting minutes. The reliability representative will update the guidelines and checklist document and write the minutes. The lead engineer will update the scorecard for the next meeting.

3.5 Final Environmental Review

The fourth and final environmental review is coupled with a safety review. During this meeting, all environmental compliance issues must be resolved. Optimally, no design changes due to environmental reasons would have been made between the last meeting and this meeting. The result of the meeting is a final guidelines and checklist document and meeting minutes. The reliability representative will finalize the guidelines and checklist document and write the minutes. The lead engineer will finalize the scorecard and create a Material Declaration Statement (MDS) packet for the product.

3.6 Postlaunch Review

Black & Decker includes a lessons-learned summary in their product development process. This document discusses what went well with the project, what didn't go well with the project, and reasons why the product didn't meet targets set in

the trigger document. The lessons-learned summary will include environmental design innovations realized during the product development process for publicity and customer questionnaires. An example of an item to be included in the lessons learned summary is a materials selection decision. Details should include what materials were considered and the rationale of the decision. The lessons-learned summary is a very important part of the DfE process because it provides future design teams with the environmental knowledge gained by the previous designers.

3.7 Feedback Loop

The completed guidelines and checklist documents and lessons-learned summaries create a feedback loop for the DfE process. Design engineers working on similar products can use this information to make better decisions immediately, and the information is also valuable when the next generation of the product is designed years down the road. Design engineers will record what environmental decisions were made and why they were made. The decision information, scorecards, and comments on the guideline document will be archived permanently. The goal is to save the right things so the information is there in the future when more feedback activities, such as a product tear-down to verify scorecard metrics, can be introduced.

4 USING DfE TOOLS

This section will explore some general DfE tools and how they should be implemented within the product development process.

4.1 Guidelines and Checklist Document

A guidelines and checklist document is a simple DfE tool that forces designers to consider environmental issues when designing products. Integrating a guidelines/checklist document within a new DfE process is a simple and effective way to highlight environmental concerns. However, it should be noted that the guidelines/checklist document needs to be company specific and integrated systematically into the product-development process. Using an existing generic, standalone document will most likely be ineffective. First, the point of a guidelines/checklist document is to ensure that designers are taking the proper steps toward achieving specific environmental objectives. Another organization's guidelines/checklist document was designed to obtain its own objectives, which may not coincide with another company's objectives. Second, obtaining a guidelines/checklist document and simply handing it to designers will lead to confusion as to when and how to use the list. Specific procedures need to be implemented to ensure the designers are exposed to the guidelines/checklist document early

16 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

in the product-development process to promote environmental design decisions. Black & Decker has systematically developed these DfE guidelines:

- Reduce the amount of flagged materials in the product by using materials not included on Black & Decker's should not use list.
- Reduce raw material used in product by eliminating or reducing components.
- Reduce the amount of flagged material released in manufacturing by choosing materials and processes that are less harmful.
- Increase the recyclability and separability of the product's components.
- Reduce the product's disassembly time.
- Reduce the amount of energy the product uses.

4.2 Product Design Matrix

The Product Design Matrix²¹ is a tool that was created with the Minnesota Office of Environmental Assistance and the Minnesota Technical Assistance Program (MnTAP). The matrix helps product designers determine where the most environmental impact of their product design occurs. Two different categories are explored within the matrix, Environmental Concerns and Life Stage. The environmental concerns (Materials, Energy Use, Solid Residue, Liquid Residue, and Gaseous Residue) are listed across the top of the matrix and the Life Stages (Pre-manufacture, Product Manufacture, Distribution & Packaging, Product Use & Maintenance, and End of Life) are listed on the left side of the matrix. The matrix is shown in Figure 2 and was adapted from T. E. Graedel and B. R. Allenby.²² Included with the matrix is a series of questions for each block. Points are associated with each question and are total for each of the 25 blocks. Then the rows and columns are totaled, providing the designers with information regarding the largest environmental concern and most environmental detrimental stage of the product life cycle. It is possible that the Product Design Matrix and accompanying questions can be varied to suit specific company needs. This tool should be used during the design review stage of the product development process so designers have an opportunity to make changes based on the results of the tool.

4.3 Environmental Effect Analysis

The environmental effect analysis was developed over time by multiple organizations, including the Swedish consulting agency HRM/Ritline, Volvo, and the University of Kalmar, Sweden. It is based on the quality assurance Failure Modes and Effects Analysis (FMEA), and the form looks much like a typical FMEA with environmental headings (Figure 3). The tool is to be used early in the product-development process by the product-development team preferably with the supervision of an environmental specialist to help with questions. First,

LIFE STAGE	Environmental Concern					Total
	1 Materials	2 Energy Use	3 Solid Residue	4 Liquid Residue	5 Gaseous Residue	
A Premanufacture	(A.1)	(A.2)	(A.3)	(A.4)	(A.5)	
B Product manufacture	(B.1)	(B.2)	(B.3)	(B.4)	(B.5)	
C Distribution, packaging	(C.1)	(C.2)	(C.3)	(C.4)	(C.5)	
D Product use, maintenance	(D.1)	(D.2)	(D.3)	(D.4)	(D.5)	
E End of life	(E.1)	(E.2)	(E.3)	(E.4)	(E.5)	
Total						

Figure 2 Product design matrix.

the team needs to identify the key activities associated with each stage of the product's lifecycle. Next, the team needs to identify the environmental aspects of the activities. Then, the team needs to identify the environmental impact associated with the environmental aspect. Some examples of environmental impacts are ozone depletion, resource depletion, and eutrophication. Next, the environmental impacts need to be evaluated to determine their significance. The evaluation technique is similar to that of the FMEA. An environmental priority number (EPN) is calculated using three variables: *S*, for controlling documents; *I*, for public image; and *O*, for environmental consequences. The variables are given a ranking from 1 to 3 based on environmental compliance, where 1 is the best possible score and 3 is the worst possible score. The EPN is calculated by adding the three scores. A fourth variable, *F*, improvement possibly, is focused on the effort in time, cost, and technical possibility of improving the product. It is based on a 1 to 9 scale, with 1 being no possibility for improvement and 9 being very large possibility for improvement. Detailed explanations of what each score means qualitatively for each variable can be found in Lindahl and Tingström.²³ After the evaluation, designers can place the results into an evaluation matrix (Figure 4) to determine what design changes should be made. Recommendations for design changes and actual design change decisions made are filled into the chart and the EPN and *F* are recalculated to ensure improvement is achieved. This form provides an excellent record of the aspects evaluated and design decisions made within the product development process.²³

Environmental Effect Analysis - EEA [The SIO-Method]																										
Part Name		Part Number		Drawing Number		Function		Date		Issue																
Project		Supplier		Info				Follow-up Date		Page No.																
EEA Leader		EEA Participants																								
Inventory Life-cycle No. Life-cycle Phase	Environmental Characteristics		Valuation				Actions				Realization															
	Activity		Environmental Effect / Aspect		S		I		O		EPN / F		Valuation		S		I		O		EPN / F		Remarks		Responsible	

Figure 3 EEA form. (From Ref. 23.)

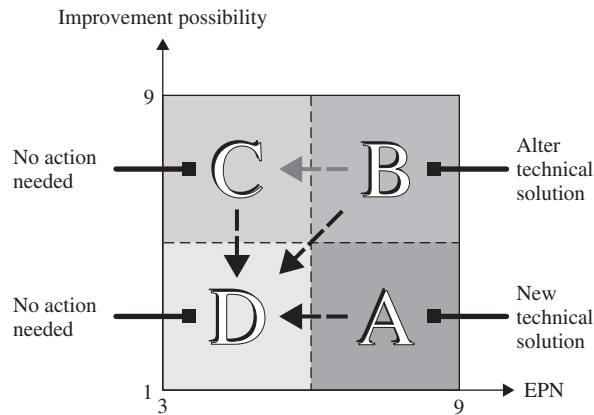


Figure 4 Evaluation matrix (From Ref. 22.)

4.4 Life-cycle Assessment

Life-cycle assessments (LCAs) are time-consuming projects that research a product's environmental impacts and conduct tests to produce environmental-impact quantities. LCAs are excellent for determining how a *current* product can be redesigned to be more environmentally benign. Unfortunately, LCAs take a long time, are very expensive, and provide information only after the design is complete. Moreover, LCAs do not help designers improve a current product's environmental impact. LCAs should not be used during the product-development process.

5 EXAMPLES OF DfE INNOVATIONS

This section provides examples of products that have been designed to reduce adverse environmental impact. Most of these products introduce increased functionality in addition to being more environmentally friendly. It is important to recognize what has been accomplished in the field of environmental design and build on this existing knowledge. By combining ideas that have been implemented in the past with their own ingenuity, designers can create new products that have minimal adverse environmental impacts, as well as adding to the environmental design knowledge base.

5.1 Forever Flashlight

The Forever Flashlight is a flashlight that does not require batteries or bulbs. Its power is generated by the user shaking the flashlight. When the user shakes the flashlight, a piece wound with copper wire moves through a magnetic field and generates power that is stored in the flashlight. Fifteen to 30 seconds of

20 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

shaking can provide up to five minutes of light. Also, the Forever Flashlight uses a blue LED instead of its bulb due to its longevity. This flashlight prevents environmental harm by reducing battery usage and provides more functionality than a typical flashlight because the user will never be left in the dark due to dead batteries.²⁴ For more information, go to <http://www.foreverflashlights.com>.

5.2 Battery-Free Remote Control

The Volvo Car Corp. and Delft University of Technology created a battery-free remote control for automobiles. This was done by utilizing the *piezo effect*, the charge created when crystals such as quartz are compressed. The remote is designed with a button on top and a flexible bottom. When the user pushes the button, the top button and flexible bottom compress the crystal, creating an electrical charge that powers a circuit to unlock the car. This prevents environmental harm by reducing battery usage.²⁵

5.3 Toshiba's GR-NF415GX Refrigerator

The Toshiba GR-NF415GX is an excellent example of a more environmentally benign product. It won the 2003 Grand Prize for Energy Conservation. In addition, this product example provides more insight than most because Takeshisa Okamoto, an engineer who designed the refrigerator, participated in an interview discussing the design of the product.²⁶ Takeshisa describes the problem with previous refrigerators in this excerpt:

To review the mechanics of earlier refrigerators, previously both the refrigerator and freezer sections were cooled by a single cooling unit. Since the refrigerator section didn't require as much cooling as the freezer section, it tended to be over-cooled. To prevent this, a damper was attached to open and close vents automatically. This would close the vents when it got too cold and open them when it got too warm. However, in the area near the vents where the cold air came out, eggs would sometimes get too cold or tofu would sometimes freeze.

Takeshisa then describes the solution to the problem and advantages of the new refrigerator:

Then the twin cooling unit refrigerator was developed. This involved two cooling units—one in the refrigerator section and one in the freezer section—using a single compressor. This system alternates between cooling the refrigerator and cooling the freezer, which allows each section to be cooled to a more suitable temperature. While the freezer's being cooled, the frost that accumulates on the cooling unit in the refrigerator section, where coolant isn't flowing, is melted once again and returned to the refrigerator section using a fan for humidification. This prevented drying, so that cheese and ham wouldn't lose all their moisture.

The technology makes it possible to cool the refrigerator and freezer sections simultaneously and to maintain two temperatures, with a major difference in temperatures between the temperatures of the refrigerator cooling unit (-3.5°C) and the freezer cooling unit (-24°C). Now, the refrigerator section is cooled by -2°C air to maintain a temperature of 1°C . This technology uses an ultra-low-energy freeze cycle that makes it possible to cool using cold air at temperatures close to the ideal temperature for the food.

Since this is the first technology of this kind in the industry, some aspects were definitely difficult. At the same time, I think this innovation was really the key point of this development. The two-stage compressor distributes coolant compressed in two stages in two directions: to the refrigerator side and to the freezer side. For this reason, the flows of coolant to each cooling unit must be adjusted to ensure optimal flow. We achieved efficient simultaneous cooling using a pulse motor valve (PMV).

From this dialogue, one can see that there is an improvement in freshness of the food due to the accuracy of the air temperature being output into the refrigeration section. This innovation also conserves electricity because of the ultra-low-energy freeze cycle. In addition, a typical engineering solution to this problem would require two compressors to achieve the final result, while this product only required one.

5.4 Matsushita Alkaline Ion Water Purifier

The Matsushita PJ-A40MRA alkaline ion water purifier²⁷ has increased functionality and decreased environmental impact compared to the TK7505 alkaline ion water purifier. The new water purifier increases functionality by allowing the user to select seven kinds of water quality (as opposed to five) based on the quality a user needs in a particular situation. The new purifier also decreases environmental impact by reducing standby power from 6 watts to 0.7 watts through division of the integrated power source into two separate power sources for operation and standby.

6 CONCLUSIONS

This chapter has reviewed a large number of DfE tools, methods, and strategies that have been developed and implemented to help manufacturing firms create environmentally benign products. From this review we draw the following conclusions.

DfE tools vary widely with respect to the information they require and the analysis that they perform. Adopting a DfE tool does not automatically lead to environmentally benign products. It is important to have DfE tools that address relevant, important environmental metrics and that provide information useful to product development decision making.

22 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

Product-development organizations need DfE processes, not just DfE tools. However, a DfE process that adds a large amount of additional analysis, paperwork, and meetings (all of which add time and cost) is not desirable. Ideally, environmental objectives would be considered in every decision that occurs during new product development, like the objectives of product performance, unit cost, time to market, and development cost. However, environmental objectives are much different than these. Instead they more closely resemble safety objectives.

One possible approach to remedy this problem is for a product-development organization to create a DfE process by expanding a process that the firm may already have in place, the safety review process. In many firms, the safety review process evaluates product safety at various points during the product development process. Therefore, combining the DfE process with the safety review process would require environmental performance to be assessed multiple times during the product-development process.

This method of incorporating the DfE process into the product development process ensures environmental performance will be evaluated at key points in the design process instead of only after the design is complete.

The safety and environmental objectives of product development organizations vary considerably from firm to firm, and each firm uses different mechanisms for addressing these concerns. Certainly, practices that make sense in one domain may be impractical in another. This chapter identifies one way to create a DfE process, something that many firms are now attempting to do, and discusses the use of this approach at a power tools manufacturing firm. The chapter's analysis of this approach is based on the similarity of the safety objectives and environmental objectives. In firms where the safety objectives and environmental objectives are quite different in scope, other types of DfE processes will be more effective. Fundamentally, though, a firm still needs a DfE process, not an isolated environmental assessment tool, to achieve their environmental objectives. More generally, a DfE process must be designed to fit within the existing patterns of information flow and decision making in the product development organization, as discussed by Herrmann and Schmidt.¹⁶

REFERENCES

1. Robert B. Handfield, Steven A. Melnyk, Roger J. Calantone, and Sime Curkovic, "Integrating Environmental Concerns into the Design Process: The Gap between Theory and Practice," *IEEE Transactions on Engineering Management*, **48**(2), 189–208 (2001).
2. Fiksel, Joseph, *Design for Environment: Creating Eco-efficient Products and Processes*, McGraw-Hill, New York, 1996.
3. Bert Bras, "Incorporating Environmental Issues in Product Design and Realization," *UNEP Industry and Environment*, **20**(1–2), 5–13 (January–June 1997).
4. Steve Ashley, "Designing for the Environment," *Mechanical Engineering*, **115**(3), 53–55 (1993).

5. Dave Allen, Diana Bauer, Bert Bras, Tim Gutowski, Cindy Murphy, Tom Piwonka, Paul Sheng, John Sutherland, Deborah Thurston, and Egon Wolff, "Environmentally Benign Manufacturing: Trends in Europe, Japan, and the USA," DETC2001/DFM-21204, in *Proceedings of DETC'01*, the ASME 2001 Design Engineering Technical Conference and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, September 9–12, 2001.
6. Mandar M. Chincholkar, Jeffrey W. Herrmann, and Yu-Feng Wei, "Applying Design for Production Methods for Improved Product Development, DETC2003/DFM-48133. Proceedings of the ASME 2003 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Chicago, Illinois, September 2–6, 2003.
7. Mattias Lindahl, "Designer's Utilization of DfE Methods." Proceedings of the 1st International Workshop on "Sustainable Consumption" Tokyo, Japan: The Society of Non-Traditional Technology (SNTT) and Research Center for Life Cycle Assessment (AIST), 2003.
8. V. Krishnan, and K. T. Ulrich, "Product Development Decisions: A Review of the Literature," *Management Science* **47**(1), 1–21 (2001).
9. J. W. Herrmann and L. C. Schmidt, "Viewing Product Development as a Decision Production System, DETC2002/DTM-34030. In ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Montreal, Canada, September 29–October 2, 2002.
10. J. W. Herrmann and L. C. Schmidt, "Product Development and Decision Production Systems," To appear in W. Chen, K. Lewis, and L. C. Schmidt (eds.) *Decision Making in Engineering Design*, ASME Press, New York, 2006.
11. *The American Heritage® Dictionary of the English Language*, 4th ed. Copyright © 2000 by Houghton Mifflin Company. Available online at www.dictionary.com.
12. Katherine J. Klein, and Joann Speer Sorra, "The Challenge of Innovation Implementation," *Academy of Management Review*, **21**(4), 1055–1080, 1996.
13. Daniel P. Fitzgerald, J. W. Herrmann, Peter A. Sandborn, Linda C. Schmidt, and Ted Gogoll, "Beyond Tools: A Design for Environment Process," *International Journal of Performability Engineering*, **1**(2), 105–120 (2005).
14. Black & Decker Corporation Code of Ethics and Standards of Conduct. Accessed February 13, 2003, at http://www.bdk.com/governance/bdk_governance_appendix_1.pdf.
15. "Directive 2004/12/EC of the European Parliament and of the Council of 11 February 2004 Amending Directive 94/62/EC on Packaging and Packaging Waste," *Official Journal of the European Union*. Accessible online at http://www.europa.eu.int/eur-lex/pri/en/oj/dat/2004/l_047/l_04720040218en00260031.pdf.
16. Environmental Protection Agency, "Terms of Environment." Document number EPA175B97001. Accessed at <http://www.epa.gov/OCEPAterms/eterms.html>.
17. Environmental Protection Agency, "Valuing Potential Environmental Liabilities for Managerial Decision Making." EPA742-R-96-003 (December 1996). Accessed at <http://www.epa.gov/opptintr/acctg/pubs/liabilities.pdf>.
18. Otto, Kevin N., and Kristin L. Wood. *Product Design: Techniques in Reverse Engineering and New Product Development* Prentice Hall, Upper Saddle River, NJ, 2001.
19. R. Goodden, *Product Liability Prevention—A Strategic Guide* ASQ Quality Press, Milwaukee, 2000.

24 Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools

20. W. F. Kitzes, "Safety Management and the Consumer Product Safety Commission," *Professional Safety*, **36**(4), 25–30 (1991).
21. Jeremy Yarwood and Patrick D. Eagan, "Design for the Environment (DfE) Toolkit," Minnesota Office of Environmental Assistance, Minnesota Technical Assistance Program (MnTAP). Accessed 2001 at <http://www.moea.state.mn.us/berc/DFEtoolkit.cfm>.
22. T. E. Graedel and B. R. Allenby, *Industrial Ecology* Prentice Hall, Englewood Cliffs, NJ, 1995). Copyright AT&T.
23. M. Lindahl and J. Tingström, "A Small Textbook on Environmental Effect Analysis" (shorter version of the Swedish version), Kalmar, Sweden: Dept. of Technology, University of Kalmar, 2001.
24. Hsaing-Tang Chang and Jahau Lewis Chen, "Eco-Innovative Examples for 40 TRIZ Inventive Principles," *The TRIZ Journal* (August 2003).
25. Power for Products, "Minnesota Office of Environmental Assistance. Accessed 2006 at <http://www.moea.state.mn.us/p2/dfe/dfeguide/power.pdf>.
26. Akane Yoshino, "Interview with Takehisa Okamoto concerning CFC-free refrigerator." Accessed January 26, 2006, at <http://kagakukan.toshiba.co.jp/en/08home/newtech131.html>.
27. Matsushita Group, "Alkaline Ion Water Purifier [TK7505] Factor X Calculation Data." Accessed January 26, 2006. http://panasonic.co.jp/eco/en/factor_x/m_pdf/fx_p21e.pdf.