Proceedings of the ASME 2009 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 - September 2, 2009, San Diego, California, USA

DETC2009-87389

A METHOD FOR DEVELOPING DESIGN FOR ENVIRONMENT GUIDELINES FOR FUTURE PRODUCT DESIGN

Cassandra Telenko
Cassandra@mail.utexas.edu

Carolyn C. Seepersad, PhD
ccseepersad@mail.utexas.edu

Michael E. Webber, PhD
webber@mail.utexas.edu

Department of Mechanical Engineering
The University of Texas at Austin
Austin, Texas, USA

ABSTRACT

Design for environment principles and guidelines help designers create greener products during the early stages of design when life cycle analysis is not feasible. However, the available guidelines are not exhaustive and a general methodology for discovering guidelines has yet to be proposed. In this paper, a method for identifying green design guidelines is presented, which aims to fulfill the need for more comprehensive guidelines. The method combines typical aspects of product design, such as customer needs analysis, with reverse engineering and life cycle analysis. Although reverse engineering is commonly applied to studies of disassembly and recyclability, the methodology and case study herein show how reverse engineering can be applied to areas of product utilization and energy consumption in particular. A general description of the methodology helps readers apply it to their own studies, and a case study of electric kettles shows how each step of the method was applied to reveal four new design guidelines.

1. INTRODUCTION

Design for Environment (DfE), or green design, guidelines serve as a means for preserving, disseminating, and translating techniques for achieving better environmental performance. Life cycle analysis (LCA) is a commonly accepted method for quantifying environmental impacts of a product, from the procurement of materials through the return of materials to the environment or processing plant [1]. However, LCA is not always feasible during the design process, nor completely accurate. It requires detailed information about products that may not be available, and it is certainly difficult to apply during the early stages of product design [2, 3]. The difficulties of LCA make it useful primarily as a retrospective tool for evaluation purposes [4]. For this reason, lessons learned from performing LCA and designing and redesigning products to meet environmental needs have been recorded as DfE principles and guidelines. DfE guidelines have been developed over the past few decades to translate the complicated analyses of life cycle impacts of products into the form of concepts that can be transferred and applied to a variety of design problems [5]. These guidelines can be applied early in the design process to help create greener concepts and save time later in the process.

Many lists of DfE principles exist, but these lists are not exhaustive and have been developed unevenly, scattered among stages of the product life cycle [6]. In previous research, the authors compiled a list of the published DfE guidelines and showed that guidelines stem from six principles of green design: sustainable resources, clean resources, minimized processing waste and pollution, minimized resource consumption during use, durability of products and components, and end-of-life processing [6]. By organizing and consolidating previous efforts, the authors discovered that extensive research has been done in the areas of product geometry and disassembly for end-of-life processing. Guidelines for improving product durability and reducing consumption during the product’s use phase were found to be less developed. Additionally, many guidelines seemed qualitative and lacked examples of quantitative validation. There is therefore a need to develop and validate guidelines in underserved and emerging areas of DfE.

In this paper, a step-by-step methodology is introduced for developing and validating new guidelines for the next generation of green products. Designers can use this method to thoroughly explore environmental design opportunities in one representative product and then apply what they learn to other products within that product class without repeating the entire analysis process. In contrast, methods for creating existing DfE principles are largely undisclosed and do not offer a thorough process for critiquing the environmental effects of designs from a variety of perspectives and, from this exploration, distilling actionable DfE guidelines for future use. Most guidelines appear to have been developed from experience in green design, by theorizing from literature, by borrowing from nature, or by using procedures tailored to a specific design problem.

For example, DfE guidelines and principles have been extracted from reviewing interdisciplinary literature and physical principles. Anastas et al., for instance, present twelve principles for design for environment [7, 8]. Their advice is so general enough to put designers in a helpful frame of mind, but offers little guidance for specific design problems. Creating principles solely from literature, as Anastas and some others do, requires extensive time to research the literature and extensive familiarity with the subjects, two advantages not available to most designers approaching green design.

Bras et al. search for sustainable guidelines and principles by deducing them from the biosphere [9, 10]. Most DfE guidelines, they argue, are based upon technically difficult and sometimes inaccurate evaluations of sustainability. They therefore propose creating principles and guidelines by translating mechanisms for natural systems to achieve balance. However, this technique is also difficult to apply to the immediate problems of defined product classes.

Examining, redesigning and comparing existing designs and possible redesigns has led to the creation of many guidelines for DfE in addition to Design for Assembly guidelines [11] and Design for Flexibility guidelines [12, 13]. Most of the procedures used to extract guidelines are either not presented or are created with limited scope to address a specific design problem or desired set of outcomes [5, 14-17]. DfE is a much broader area than assembly or flexibility and so requires a methodology that is not limited to disassembly metrics or the life cycle effects of changing materials and components. For example, design for disassembly procedures [18] usually do not include customer needs analysis. Not incorporating such steps means not only missed opportunities, but also difficulties in dealing with customer needs, such as product durability and usage. Possibly a direct result of this trend, most product durability guidelines address areas of maintenance and upgradeability rather than strict durability. Therefore, the methodology proposed here combines well-known needs analysis and reverse engineering techniques [19, 20] with existing DfE guidelines and LCA metrics to create a holistic method for rethinking product design and creating guidelines that can be used in future concept generation.

Additionally, not all of the guidelines presented in the literature have been validated or explored using life cycle analysis. For a guideline to be useful, it is important that designers are aware of how a change in one phase of a product can cause repercussions in other phases of the lifecycle [10]. For example, the difference between a thermoelectric refrigerator and a vapor compression refrigerator exemplifies the tradeoffs between efficiency and other environmental effects. Although an old, vapor compression refrigerator may consume a fraction of the electrical energy of a new, thermoelectric refrigerator of similar volume, the thermoelectric device is much lighter, decreasing energy use in transportation, and does not use hazardous refrigerants, decreasing non-energy, toxicological impacts. Because of the complexity of environmental effects, this paper proposes a fluid and complete methodology for analyzing existing competing products with regards to their use in context, their purpose, their engineering specifications, and their life cycle tradeoffs. The method focuses on the usage stage of the life cycle because it is easier to understand the repercussions of design decisions by isolating changes in one stage of the life cycle and then investigating the effects of these seemingly isolated changes on other stages of the life cycle.

In the next section, a methodology is presented for developing green design guidelines. Because the method is centered on product utilization, it is best applied to assembly, disassembly, extending the useful life, and improving the sustainability and efficiency of resources during use. In section three, the methodology is applied to a case study of the energy efficiency of thermomechanical products. Application of the method results in a set of four design guidelines that can be applied to the design of future thermomechanical products.

2. METHODOLOGY

As shown in Figure 1, a methodology has been designed for deriving DfE principles from a combination of reverse engineering, needs analysis, and life cycle analysis. Reverse engineering forms the backbone of the method; it provides a means for systematically analyzing the requirements, architecture, and functionality of an existing product [20]. Several steps are taken to customize a reverse engineering methodology for this application. First, customer needs are extended to encompass additional needs relevant to environmental performance. Green needs, as they are called in this paper, are more comprehensive than customer needs. These needs describe the environmentally friendly and environmentally harmful aspects of a product from the life-cycle perspective. Green needs serve as prompts for potential green redesign opportunities. Green needs are identified by integrating results from customer needs analysis with life-cycle analysis and experimentation. Life cycle analysis serves two purposes in the proposed method. First, it is implemented as part of the reverse engineering process to help identify environmental concerns with respect to existing products. Then, it is applied again at the end of the method to evaluate and understand guidelines derived from the study.

Figure 1 outlines the steps of the methodology. In step zero, a set of products is selected to study. Specific products are chosen based upon their functional relevance to the product being (re)designed. These products should embody different working principles or architectures to achieve the same function. For example, a designer focused on portable refrigeration devices might select one or more miniature vapor-compression refrigerators and thermoelectric coolers with different architectural arrangements, sizes, controllability, etc. Good sets of products provide interesting variability with respect to architecture, user interactions, materials, and/or solution principles. They should also be expected to exhibit a range of performance in the area of environmental concern. However, the study must remain focused on the functionality of interest; for example, a sprinkler not only waters, but automatically spreads water evenly, so it should not be compared with a bucket or a plain water hose.

In step one, an initial set of green needs is created by investigating user requirements and the usage context. Personally operating the products as well as surveying user comments allows one to interpret and record user needs and potential green needs. As shown in the flow chart, articulated-use interviews are one good method for soliciting feedback and discovering latent customer needs [19]. Activity diagrams are also good supplemental tools to map the utilization process and interactions with the environment, other products, or concurrent activities [19]. If the green redesign effort is focused on a specific life cycle stage or motivator (e.g. resource use, durability, or recyclability.), it is useful to focus these activities on that aspect of the product. The result of step one should be not only an initial set of green needs, but also a good understanding of the product in the context most applicable to the study motivators.

In step two, the researcher revises and expands the green needs by analyzing the products from a conceptual and functional perspective. Black box modeling is one method for focusing on the primary function of the product and neatly relating the material, signal and energy flows that enter and leave the product [21]. Black box diagrams help designers distinguish necessary flows from process choices (i.e. the input energy might not need to be electrical.) Building on the black box models, function structures map the necessary and relevant intermediate functions of the product(s), following the input flows through the product to their output flow forms. Function structures are useful ways of disembodying and opening the design discussion to alternative solutions from a subsystem or component standpoint [22]. At this point, the black box and functional models may be hypothesized, since the product has not yet been disassembled.

After creating the hypothesized function structures and black box models, it is helpful to sketch a schematic predicting the components used to fulfill those functions. Creating one or more possible architectures is one way to think about how relevant needs might be met or missed by the products' designs. Predicting product architecture then makes it possible to compare the products with existing green design guidelines and further identify good, bad or missed design opportunities as one would with a checklist [23]. The challenge at the conclusion of step two is to brainstorm a list of green design needs that is as comprehensive as possible, so that these needs can be quantified and addressed in the following steps. By step three, there should be a succinct set of green design needs.

FIGURE 1: METHOD FLOW CHART FOR CREATING GUIDELINES

In step three, the researcher quantifies the engineering specifications that relate to the products' green design needs. The house of quality (HOQ) is a well-known tool for correlating customer needs or performance criteria, with measurable engineering specifications [19, 24]. The goal is to correlate performance with measurable design characteristics—such as dimensions and performance parameters—that can be changed. For example, a green need for a sprinkler may be to eliminate waste of water. Two engineering specifications that relate to the sprinkler's need are the amount of water that does not reach the desired watering area and the amount of over-watering in desired areas. After the engineering specifications affecting the green performance of the products are identified, they can be measured with respect to the motivating form of utilization. For example, the durability of a cell phone could be measured by dropping it or employing other commonly observed actions. By measuring the relevant specifications, either static or dynamic, it is possible to deduce causes and effects for good or poor green performance in product utilization. These insights will take the form of new green needs as well as possible guidelines for satisfying green needs already recorded in the previous steps.

At this point in the study, green needs will have been revealed from three perspectives: usage, abstract functionality, and engineering details. An initial set of potential new guidelines will be taking form as well. It is important that these guidelines are recorded in a form that is as actionable, general, designer oriented, and reflective of best practice as possible [6].

Step four, the dissection of the products, highlights final aspects of the products' architectures relevant to their performance. Disassembly and discovery of the actual product architectures may reveal more or fewer functions than previously envisioned and may show that functions have been approached in more or less innovative ways than predicted. Creation of a Bill of Materials (BOM) from the disassembly is necessary to become fully familiar with the design and perform life cycle analyses as well as to create the basic BOMs for redesigning in step seven. Because operations are now embodied, the list of possible new guidelines can be expanded and clarified.

Step five, the life cycle analysis of one of the existing products, reveals the relative impacts of design decisions. Life cycle analysis helps prioritize redesign goals and, hopefully, avoid worsening the environmental impacts of the product via redesign. The scope and accuracy of the analyses is limited to available data, but should be as complete as possible and repeatable for the redesign process in step seven. For now, lessons from the LCA will prioritize the needs and guidelines already brainstormed and help inform the redesign tasks.

In step six new product concepts are proposed with architectures and guidelines that help meet the previously identified green design needs. Concept generation can be achieved using any number or combination of brainstorming methods. A survey and explanation of relevant techniques are given by Otto and Wood, and Pahl and Beitz [19, 21]. One method for sketching concepts is 6-3-5, during which six participants individually build ideas from each others' concepts. It might be helpful to enlist one or more uninvolved designers in team-based concept generation activities, to reduce the likelihood of design fixation.

In step seven, the generated concepts and existing product examples are used to refine and finalize the list of guidelines and validate them with life cycle analysis. Guidelines are distilled from the concepts by discerning how the designer tried to better meet the green needs with each embodiment. These guidelines are then used to revise the dynamic list from the previous steps. Finally, these guidelines are reinforced by finding analogies in other product embodiments that exist outside of the domain or set of products being researched. This exploration of partially related products will help to mold the final guidelines into a more generally applicable, but still actionable form.

Once the guidelines are established, two design concepts and BOMs must be created for each guideline, to represent the product *before* and *after* implementation of the guideline. LCA is applied to each concept and BOM. By comparing LCA results before and after implementation of each guideline, designers can assess the potential impact of each guideline for a specific class of products. The pre-guideline concept, BOM, and LCA is based on the results of step five, assuming that the existing product does not yet embody the guideline. The post-guideline concept and BOM is based on the redesigns generated in steps six and seven, and those BOMs are used for LCA to investigate whether applying the guidelines improves upon the original design. It may be necessary to carry out further experiments, calculations or modeling to update the key engineering specifications that contribute to the life cycle inventory of the concept. The results of the LCA-based validation are strictly applicable only to the class of products investigated in the study. They may not be generalizable to other product domains without further research, but inferences can be drawn with respect to expected environmental conflicts or improvements in related applications. The result is a set of new design guidelines that can be used for designing new products in the product domain of interest without additional LCA. The guidelines are applicable during the early stages of design, when important decisions are made and LCA is not feasible.

As described in the following section, the method is applied to a case study of three different electric kettles. The case study shows how each of the steps are applied, as well as how insights and understanding of green design develop over the course of the study. Guidelines are developed for reducing the kettles' resource consumption during use.

3. CASE STUDY: ELECTRIC KETTLE

Electric kettles were chosen as an interesting electromechanical product with two valuable consumables: water and energy. Many studies have already been presented that use product dissection and redesign steps to reveal guidelines for product disassembly and recycling, but a study of electric kettles in use shows how the proposed methodology can help generate guidelines for reducing resource consumption during the consumer-use phase of the life cycle. This section documents the application of the step-by-step methodology to the electric kettles and the significant insights obtained from each step.

3.1 Step Zero: Select Products to Study

Three kettles were selected based upon noticeable variations in energy-related functions. Table 1 lists the three products and summarizes their differences in terms of heating elements, insulation, power ratings, and other aspects influencing energy efficiency. A Proctor Silex kettle was chosen because it was the cheapest, lowest power, and smallest kettle available and had an internal coil heat exchanger. A Capresso H2O Plus was chosen because it was made out of glass rather than traditional plastic and had a central, spherical heating element. The Braun was selected because it was the most popular model and had a flat plate heat exchanger along the bottom. Each kettle offered different advantages, from the thicker, possibly better insulating, walls in the Capresso kettle, to what appeared to be a more efficient, circulating heat exchanger in the Proctor Silex. The efficiency impacts of different powers or heating element configurations were unknown, but it was assumed that better prevention of steam loss (e.g. sealing lids and spout covers) would improve energy efficiency.

Kettles	 Braun AquaExpress	 Capresso H2O Plus	 Images from Amazon.com Proctor Silex Electric Kettle
Energy Pros	Smallest Viewing Area, Has a Spout Cover, Lip to Seal Lid.	Thickest Walls, Heating Sphere has good surface area and keeps hottest water centered.	Heating Coil Seems to Encourage Circulation.
Energy Cons	No Alarm.	No Alarm, Poorest Spout Cover.	Thinnest Walls, No Alarm, Heating Coil Keeps heat at Walls.
Insulating Material	Plastic	Glass	Plastic
Heating Elements	1360 Watts	1340 Watts	930 Watts

TABLE 1: PRODUCTS WERE CHOSEN BY THEIR FUNCTIONAL DESIGNS

3.2 Step One: Gather Customer Needs and Usage Patterns

After the kettles were selected, they were assessed through exploratory use and customer feedback to discern a list of possible user needs. The process resulted in three main observations. First, the kettles would boil shortly before turning off and some users would impatiently stop the kettle early, as noted in informal customer interviews. Closing the gap between shut off and boiling presented an opportunity to reduce energy. Second, customer reviews indicated that users sometimes forget to check their kettles if there is not a noticeable shutoff signal when the water is boiled. Energy would be lost as the forgotten water is left to cool, and additional energy would then be consumed to re-heat the water. Third, it seemed as though a significant amount of energy was lost as steam escaping from the kettles, sometimes enough to risk burning the users. Most of the kettle designs shared these aspects with the exception of heat lost as steam. Only this last observation had been foreseen in step zero, as the other observations required more knowledge of how the kettles are used in a daily setting.

3.3 Step Two: Predict Architecture and Functionality

A black box diagram was created to focus on the primary task of boiling water and the energy, material, and signals that were chosen or necessary to meet this task.

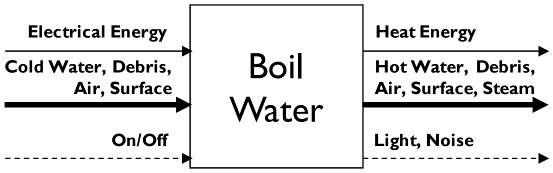

FIGURE 2: THE BLACK BOX MODEL OF AN ELECTRIC KETTLE SHOWS GENERALIZED PROCESS CHOICES

The kettles' black box representation, FIGURE 2, made no specific assumptions about the inner architecture of the kettles and instead brought attention to electrical energy, water, and user inputs as well as the desired heat and hot water outputs. Noise was noted as an output to indicate that some of the kettles made a small click, but also to represent the green need for better notification from step one. The choice of electrical energy as an input could be modified; since the desired output is heat, it is possible to use any form of energy that may already exist as heat or to create heat. Aside from the energy flows, the flows into and out of the kettle appeared to be entirely necessary and could not be made greener by changing their form. However, amounts could be modified. For example, heat energy might not be removed as an output, but it could be reduced as much as possible. The amount of each material and energy intake can be matched as closely with the desired output as possible. This insight led to the construction and study of a p-diagram.

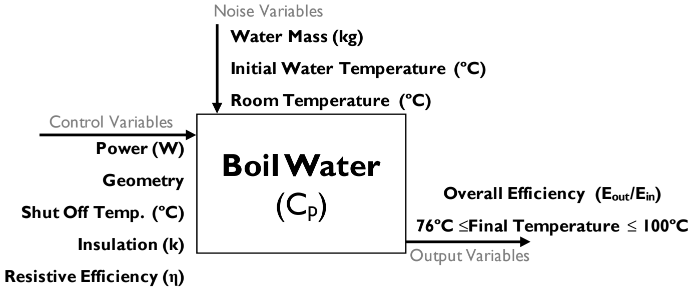

FIGURE 3: P-DIAGRAM

Based on insights obtained from the black box, a p-diagram, FIGURE 3, of noise and control variables was created. One can see from the diagram that it maintains perspective at a level of abstraction near to that of a black box, but allows the study of variables relevant to the product's functionality, such as quantities of water or heat energy. P-diagrams are useful for identifying possible noise variables that affect operation but are outside of the designer's control and control variables that can be modified to best compensate for noise and achieve a desired output. The water intake was not recognized as modifiable by the p-diagram and in the actual design is only affected by measuring gradients marked on the kettles. The overall efficiency was included in the p-diagram as the desired green output to be maximized. This performance variable depended upon two other variables: the input power and final temperature. Researching the final output temperature showed a range of temperatures for different task requirements (i.e. heating cooking water quickly or steeping teas), noted in the p-diagram. The current kettle designs had no option for the user to set the desired final temperature, and it was decided that such capability should be included in the predicted architecture to help identify a more complete set of needs and guidelines.

Recognition of the noise variable, the mass of the water, and the control variable, the shut off temperature, allowed for the creation of a function structure that included more relevant functions than a function structure built from needs, usage patterns, and the black box alone. The expanded function structure included not only the basic functions for boiling water, but additional processing functions that can contribute to the efficiency of the kettles. These functions are shaded in the hypothesized function structure in Figure 4. The expanded functions addressed the variability in final temperature and water mass and met a new green need for the kettles to be tuned for certain processes, dynamically or at the beginning of the process. The existing functions of 'stop thermal energy' and 'measure thermal' met the previously identified green needs of stopping steam and stopping heating at boiling. The need for better notification was not modeled, as existing notification was modeled as the 'on light.' The function structure revealed locations of heat loss and presented possible new architectures that proved useful in step six of the methodology.

Before finalizing the list of green needs for redesign and initiating a list of possible new green design guidelines, it was necessary to compare the kettles with existing green design guidelines to make the list of needs as extensive as possible. The existing guidelines for resource efficiency are shown in Figure 5.

The kettles were analyzed using those guidelines, as well as guidelines specifying renewable and clean forms of energy. It was noted how each product met, failed to meet, or obviously had an opportunity to implement each guideline. Many of the guidelines seemed to be satisfied by the products or inapplicable to the current kettle designs. Two missed guidelines were those for choosing alternative, cleaner energy sources and integrating with available resource flows, as the kettles imported electrical energy from the wall outlet and did not use waste heat or solar energy. The kettles also did not implement fail safes against heat or material loss, as steam escaped from the kettles and the material of the kettle walls had poor insulation.

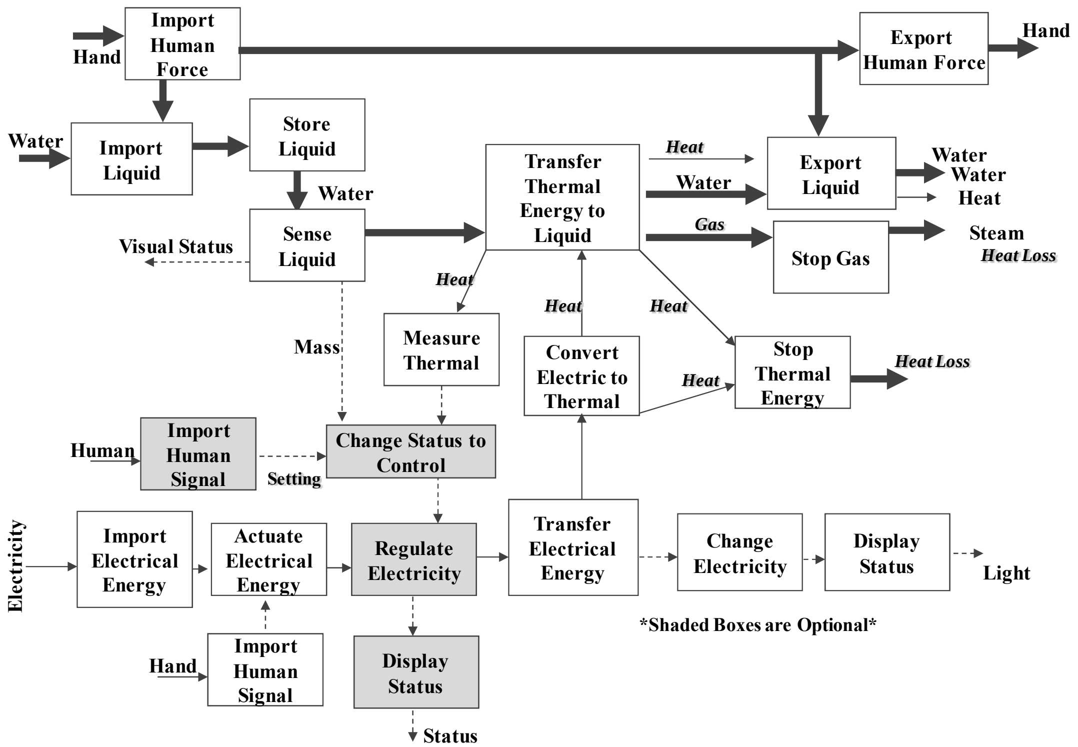

FIGURE 4: THE EXPANDED FUNCTION STRUCTURE SHOWS ALL OF THE RELEVANT FUNCTION

D. Ensure efficiency of resources during use by:

1. Implementing reusable supplies or ensuring the maximum usefulness of consumables
2. Implementing fail safes against heat and material loss
3. Minimizing the volume, area and weight of parts and materials to which energy is transferred
4. Specifying best-in-class energy efficiency components
5. Implementing default power down for subsystems that are not in use
6. Ensuring rapid warm up and power down
7. Maximizing system efficiency for an entire range of real world conditions
8. Interconnecting available flows of energy and materials within the product or between the product and its environment
9. Incorporating part-load operation and permit users to turn off systems in part or whole
10. Using feedback mechanisms to indicate how much energy or water is being consumed
11. Incorporating intuitive controls for resource-saving features
12. Incorporating features that prevent waste of materials by the user
13. Defaulting mechanisms to automatically reset the product to its most efficient setting

FIGURE 5: GUIDELINES FOR RESOURCE EFFICIENCY DURING USE [6]

From the first three steps of the methodology, several potential opportunities for improvement were identified as green needs and guidelines:

1. **Import Cleaner Energy Forms**
   Guideline already exists
   Because all three kettles were powered from a wall outlet, all three kettles were subject to a mixed power grid with no assurance of clean or renewable energy. There was therefore an opportunity to implement human power, ambient energy or other renewable sources of power.
2. **Reduce Energy Loss**
   Guideline already exists
   The thickness and material of the kettle walls varied both within and across the designs. It is therefore possible to increase the insulation of the kettles. Additionally, each kettle allowed steam to escape, suggesting that there may be a way to relieve pressure and simultaneously prevent heat, or steam, from escaping.
3. **Improve User Notification**
   Possible New Guidelines:
   Notify the user when operations are finished.
   Prevent the user from unnecessary operations.
   Notification that the kettle water has reached the appropriate temperature was limited to a click of the on/off switches and a light turning off. Reviews and trials indicated that the kettle might be forgotten long enough that the user would be compelled to reheat the contents and "waste" energy.
4. **Optimize Individual Runs/Processes to Outcomes**
   Possible New Guideline:
   Incorporating tuning capabilities for certain processes, dynamically or statically
   The p-diagram and expanded function structure revealed that energy efficiency could be improved by compensating or tuning for the amount of water in the kettle or the desired water temperature. No kettle appeared to have such capability.

3.4 Step Three: Quantifying Green Design Specifications

In step three, experiments were conducted to quantify the green design specifications. The specifications were obtained from the green needs, p-diagram, and potential guidelines revealed in previous steps.

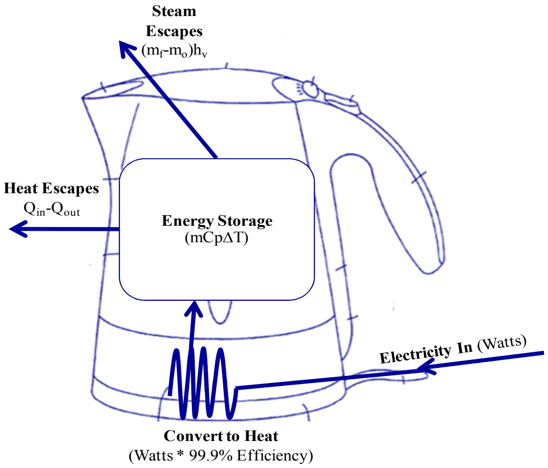

FIGURE 6: ENERGY FLOWS INTO AND OUT OF THE KETTLE WERE CALCULATED

The basic operation of each kettle is shown in Figure 6 and dictated how measurements were taken during the kettles' operations. Important performance parameters included the overall efficiency of each kettle (ratio of electrical energy consumed to thermal energy transferred to the water) and corresponding inefficiencies such as escaped steam and heat. Measurable variables included electrical energy consumption, water temperature, and water mass. The water temperature of each kettle was measured during heating, along with the electrical energy imported. Each experiment was repeated for three different masses of water, specifically one, two and three mugs (0.3-1kg) in the case of the Proctor Silex model and two, three, and four mugs (0.6-1.6kg) in the case of the larger Capresso and Braun kettles. The mass of the water inside the kettle was also measured before and after heating to estimate the thermal energy lost as steam. The electricity was measured in watts from the wall outlet and assumed to be converted to heat at an efficiency of 100%. This heat was then either stored in the water, lost through the walls of the kettle, or transported out of the kettle by steam. The temperature change of the water was used to calculate the energy stored by the water. Subtracting this value from the imported and converted energy provided an approximation of the thermal energy loss during heating.

Overall, the kettles exhibited similar heating and cooling performances except with respect to shut-off behavior. Steam loss was estimated at about 1% from measurements and therefore neglected. However, as shown in Table 2, all three kettles were observed to heat past visual boiling, resulting in varying overall efficiencies. Visual boiling seemed to consistently occur at a temperature of 95ºC. If each kettle stopped heating at the visual boiling point of 95ºC, their efficiencies would be nearly identical, as illustrated in the last two columns of Table 2. The Capresso exhibited the highest efficiency because it stopped heating at a much lower temperature than its competitors. In contrast, the Braun exhibited the lowest initial efficiency because it shut off after extensive overboiling.

From this experimental study, it was apparent that the physical and architectural differences between the kettles had very little effect on the overall efficiency, relative to their shut-off characteristics. The p-diagram corroborates the discovery that incorporating better logic (the ability to tune the process to the desired outcomes) provides a significant increase in energy efficiency as well as a reduction in energy use. Overheating is especially undesirable because the efficiency of the heating process was observed to decrease as the water temperature increased, due to factors such as temperature dependent convection and radiation heat loss from the sides of the kettle. A new guideline was proposed, *optimizing the heating rate and time to reduce overall energy use*.

		Example Results for Heating 1kg of Water (3 mugs)			
Model	Average Run Specs	Total Electrical Energy Input	Energy Effic. w/Overheat	Energy Effic. w/o Overheat	Energy Saved by not Overheating
Braun	Runs at: 1360 Watts Overheats for: 66 Seconds	482 kJ	70%	86%	18%
Capresso	Runs at: 1343 Watts Overheats for: 16 Seconds Overheat	400 kJ	84%	85%	2%
Proctor Silex	Runs at: 928 Watts Overheats for: 70 Seconds Overheat	422 kJ	79%	84%	7.30%

TABLE 2: THE ENERGY STUDY SHOWS THE ENERGY SAVED BY HEATING TO 95ºC

At the end of step three, the operations of the kettles had been thoroughly explored to reveal five green needs and four potential green design guidelines. Many of these insights were predicated upon assumptions about the inner architecture and functionality of the kettles. The next step was to disassemble the kettles, to uncover their precise architectures and to investigate whether additional guidelines may be needed or embodied in one or more of the kettles.

3.5 Step Four: Dissect the Product

Disassembly of the kettles revealed that the internal components were similar for all three designs. The architecture and functionality of the kettles had been predicted relatively accurately and no further green design insights were gained by observing the actual components. However, teardown of the kettles did contribute to the creation of a bill of materials (BOM) for each kettle. The BOM made it possible for life cycle analysis of the products. Because the designs were remarkably similar, the BOM for the lightest and smallest kettle, the Proctor Silex kettle, was used for the life cycle analysis and as the base design for comparison in the final steps of the methodology.

3.6 Step Five: Perform a Life Cycle Analysis

Before brainstorming new concepts, an LCA of the Proctor Silex kettle was performed to investigate the most impactful aspects of the kettle's design. As part of the LCA, the functional unit of the electric kettle had to be estimated. This functional unit was determined from a survey of 16 kettle users. From the survey results, the kettle was assumed to boil 2.5 mugs of water, 8 times a week for a lifetime of four years. The experiments in step three specified the amount of energy that is required for 2.5 mugs of water. The collection of operating data for the device in the stage of interest, the use stage, was complete. Exact data for each stage of the kettle's life cycle, such as manufacturer's data, were unavailable, making a complete LCA impossible. Instead, the BOM information enabled an approximate life cycle inventory and analysis with the help of GaBi and SimaPro software. Transportation of the parts, materials and final kettle were not within the scope of the LCA as this data was completely unknown. For end of life, it was assumed that no components were recycled [25, 26]. The EcoIndicator 99 hierarchist approach was used to create a composite environmental impact score known as the EcoIndicator (EI) Score in units of millipoints (mp) [27].

Life Cycle Stage	Contribution to EcoIndicator Score
Manufacturing	2%
End of Life	1%
Useful Life	97%

TABLE 3: THE USEFUL LIFE OF THE KETTLE DOMINATED ITS EI SCORE

Because the kettle contained few components and used a significant amount of energy during its useful life, the use stage impacts (energy impacts) dominated the kettle's EI score, as shown in TABLE 3. From these results, it was clear that new designs with lower shut off temperatures would most likely result in an overall net benefit over the product's lifecycle. The LCA verified that energy consumption is a priority for designs of products similar to the kettle that import significant amounts of energy and incorporate only a few, simple components (especially if the components are associated with relatively benign materials and manufacturing processes). In other cases this dominance may not exist, but the LCA should help redirect future design preparations. At this point in the case study, the analysis process ended, and results were used to generate new, greener concepts and to finalize and validate the guidelines.

3.7 Step Six: Generate Concepts

The concept generation process began with a brainstorming step, in which researchers created a list of different methods for measuring temperature, as this function was revealed to be paramount in all of the previous steps. The list included bimetallic strips, as already used in the kettles, as well as thermocouples and Galilean thermometers. A list of different methods was also created for notifying a user of shut-off, including devices for hearing, smelling, and seeing.

A group of six graduate engineering students in the areas of manufacturing, design, and thermal systems was then enlisted to create new kettle concepts that save energy. The participants were shown the kettles being studied, the predicted function structure, the black box diagram, the p-diagram, and the list of pre-existing guidelines, as presented in Figures 2-6. They were also presented with the final list of green design needs: Incorporate Clean Energy Forms, Reduce Energy Lost During Heating, Provide User Notification, Incorporate Individual Run/ Process Optimization, and Stop the Process at the Exact Temperature Desired.

One session of 6-3-5 was carried out. Each participant received a uniquely colored pen and a piece of butcher paper. They were each given twenty minutes to devise three novel concepts for the kettle that meet one or more of the green needs. After the first twenty minutes, the papers were rotated to a new member of the group, who spent eight minutes modifying the concept. At the conclusion of the session, at least 18 different concepts had been created. These concepts were then used in the final step of the study for updating and validating the green design guidelines.

3.8 Step Seven: Update + Validate Green Design Guidelines

The concepts from step six were analyzed for features that might be useful for green redesign of the electric kettle. For each feature, one representative concept was identified and assessed for its potential as a guideline. Figure 7 shows some of the more common features and product-specific guidelines that the participants employed in their redesigns. Many of the kettle design concepts provided device controls for user adjustment of variables such as the amount of water, the stop temperature, and the start time. While many of the concepts were clearly viable, some were infeasible for various reasons. For example, some concepts used gravity or pressure from locking the lid to assist in boiling the water faster. This concept was most likely inspired by the pre-existing guideline for "employing ambient energy." However, the resulting concept was deemed unsafe, and no feasible, alternative concepts were based on the guideline.

After analyzing the set of concepts, it was concluded that no new, actionable guidelines could be extracted from the results of the 6-3-5, but some of the concepts served as representative embodiments of the guidelines already suggested by the study. The existing list of potential guidelines was then updated with the representative embodiments, along with similar examples from products unrelated to the electric kettles. The final set of new guidelines is presented in the remainder of this section (3.8.1 – 3.8.4), along with the process for validating them (3.8.5).

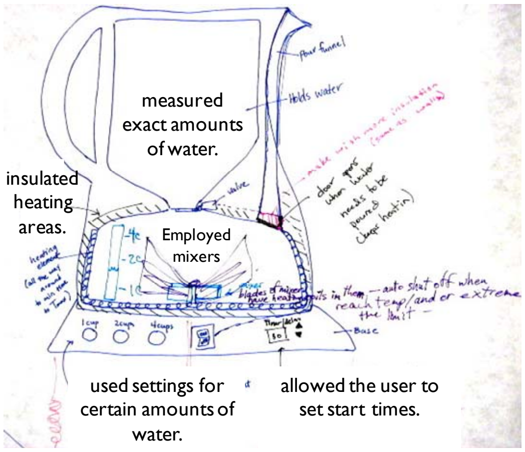

FIGURE 7: ONE 6-3-5 CONCEPT INCORPORATED MANY SOLUTIONS

3.8.1 New Guideline 1: Minimizing the quantity of resource use by optimizing its rate and duration

In the case of the kettles, energy consumption was minimized by reducing the final temperature of the water, thereby lowering the total amount of energy transferred to the water. A positive side effect of this modification was a reduction in the duration of heat transfer to the water, and specifically, elimination of a significant period of heat transfer to the water at high temperatures (near boiling). At high water temperatures, heat transfer to the environment (via conduction through the kettle walls and radiation and convection to the surrounding environment) is significantly higher, regardless of the kettle architecture. Another means of reducing the energy loss to the environment would be to simply increase the power input of the kettle, thereby heating the water more quickly and reducing the duration of high-temperature heat transfer to the surrounding environment.

Several products adjust rates and durations of resource use to maximize efficiency and minimize overall resource use. Examples include tankless water heaters, low flow shower heads, and advanced washing machines. Tankless water heaters save energy by heating water at a high rate only at the instant it is needed, rather than maintaining the temperature of a large tank of water. The DOE estimates that such systems use 28% less energy than a 40-gallon tank heater (DOE, 2004). Low-flow shower heads are designed to use control variables to minimize the impact of noise variables. It is very difficult to control the length of a shower, but the amount of water wasted can be minized by reducing the water flow to minimum levels. Additionally, in some hostel or public showers, the showers incorporate automatic shut offs that require the user to restart the water at selected intervals. This increases the likelihood that the water is only used when necessary and that the user will take a shorter shower. Finally, the DOE recommends using high spin washers to clean clothes. By increasing the rate of energy in the spin cycle, more water is purged from clothing. Putting less wet clothing into the dryer then decreases drying time and increases overall efficiency. From the examples, it is clear that this principle can be applied to any number of energy or material flow cases and can even be applied in combination between products, such as a washer and a dryer, that are linked by common activities.

3.8.2 New Guideline 2: Incorporating automatic or manual tuning capabilities

The second new guideline, incorporating automatic or manual tuning capabilities, came from observations that the duration of water heating (and corresponding energy use) could be further reduced by allowing the user to set a desired water temperature. For example, it is possible to reduce the duration of heating by limiting the temperature to when an observer sees boiling at 95ºC. However, even more savings could be enabled if the user were allowed to select a specific stopping temperature (e.g., 80ºC for hot chocolate). This guideline is exacted in multi-flush toilets, programmable thermostats, and some washer and dryer systems. A design for a multi-flush toilet has two presets, light and heavy, depending upon the force needed to flush the toilet bowl. These more appropriate settings prevent the user from excessively flushing a regular low flow toilet while reducing water consumption at the same time. Programmable home thermostats allow inhabitants to regulate the temperature of their homes automatically. Additionally, some programmable home thermostats are connected with the electricity provider for demand-side management, allowing the provider to create more efficient load curves during peak times, reduce the number of power plants required, and even curb excessive cooling or heating by customers. Finally, returning to the example of washers and dryers, the DOE reports that upgraded motors in washing machines and dryers with variable settings that adjust operation to the magnitude of the clothing load can deliver up to 60% savings in energy efficiency, while fixed-load devices are limited to 15% savings [28]. It seems that automatic and even manual tuning can provide a simple means for significant reduction in resource use.

3.8.3 New Guideline 3: Using feedback mechanisms to inform the user of the current status of the process

Feedback mechanisms were devised to inform the user of the current status of the heating process (i.e. temperature) and to prevent the kettle users from reheating water. This solution is a measure of performance, a value derived from customer needs and the product's function, and should be distinguished from solutions that monitor energy or water input, as described by Guideline D-10 in FIGURE 5. Also, a feedback mechanism could allow a user to prematurely end the process when the water reaches a desirable temperature, or realize that the water does not require reheating if it has been allowed to cool. Ovens are another example of successful use of feedback mechanisms to save resources, particularly energy. Many new ovens provide temperature readings and alarms to notify users that the oven is preheated. Additionally, heat can be lost as chefs open the door to consistently check the status of food within the oven. Many ovens have lights inside and windows in the doors to allow users to check food without losing valuable heat.

3.8.4 New Guideline 4: Creating separate modules for tasks with conflicting requirements/solutions

During the experimentation process, IR cameras indicated that less heat radiated from opaque plastic than from the clear plastic used for measuring the water level in the Braun and Proctor Silex kettles. The proposed solution was to separate the section for measuring water from the section for heating water. This separation of tasks to increase efficiency is similar to the concept behind electric hybrid vehicles. Electric hybrid vehicles switch between being an electric motor and a gasoline engine to operate both at their most efficient speeds. Another example of this guideline is exhibited by the EcoKettle, which has separate sections for storing and heating water. This separation allows users to store as much water as they like in the kettle, but avoid heating more water than needed.

3.8.5 Quantitatively Investigate Each Guideline with a New LCA

Based upon the concepts generated in step six, the four new guidelines were distilled into four separate representative designs so that the change in environmental impact could be estimated. The energy saved by each improvement was either calculated from the experimental results (as in guidelines #1,2) or derived from a single-user home study. Each previously unpublished guideline is presented in Table 4 along with the redesign, component changes, and estimated change in energy and environmental impacts. The objective of this analysis was to isolate each guideline as much as possible and investigate the necessary conditions for overall improvement of a product's environmental impact. Specifically, EcoIndicator assessments were used to evaluate whether the guideline lowered the environmental impact of the product in the use stage and if so, whether the improvement was negated by tradeoffs in other life cycle stages such as raw material production and manufacturing.

As shown in Table 4, simply specifying an earlier shut off according to guideline #1 resulted in a reduction of environmental impact. There were no changes in other aspects of the product's life cycle.

For guideline #2, the additional components led to a potential increase or decrease in environmental impact. If the user utilized the manual tuning capability consistently to the lowest possible setting, 76ºC, the kettle's energy use and overall environmental impact would be substantially lowered. However, the addition of tuning capabilities gives rise to environmental tradeoffs with respect to the additional energy, chemical, and waste effects of mining, manufacturing, and disposing of the extra components. Therefore, a net increase in environmental impact would occur if the user did not take advantage of the manual tuning capability. Interestingly, if manual tuning were combined with a lower default setting, lower impact is guaranteed in the case of electric kettles when compared to the original design.

#	1	2	3	4
Guideline	Minimizing the quantity of resource use by optimizing between its rate and time.	Incorporating automatic or manual tuning capabilities.	Using feedback mechanisms to inform the user of current status of the process.	Creating separate modules for tasks w/conflicting requirements/solutions.
Redesign	Earlier Shut-Off (95°C)	User Sets the Shut-Off Temperature (76°C)	Displays Current Water Temperature	Measuring Cup for Water
Replaced Component	Bi-Metallic Switch	Bi-Metallic Switch	N/A	Remove Viewing Area
Additional Components	New Bi-Metallic Switch	Thermocouple, Circuit Board, Dial/Potentiometer, Switch	Thermocouple, Circuit Board, Display Screen	Measuring Cup
Energy Saved (1 kg, 3 mugs)	52 kJ	164 kJ	37 kJ	2kJ
	12%	38%	36%	0.50%
Change in E.I. Score	-624 mp	-1700 to +249 mp	-245 to +197 mp	-10 mp
	5% Reduction	14% Reduction to 2% Increase	2% Reduction to 2% Increase	0.08% Reduction

TABLE 4: EACH OF THE GUIDELINES WAS MATCHED WITH A NEW KETTLE DESIGN AND ENVIRONMENTAL IMPACT

Guideline 3 led to the addition of a temperature display. The user could use this display if they had forgotten about their hot water and arrived after a time of cooling. The savings calculated show the potential savings from not reheating the water if it has not cooled to too low of a temperature. Additional savings could be seen if the user uses the temperature display to help turn off the kettle earlier. Similar to the solution from guideline 2, the user may or may not engage in energy saving behavior.

Guideline 4 led to both a smaller amount of energy savings and a potentially smaller increase in impact due to the extra components. Therefore, it was most advantageous to combine guidelines 1 and 2, while guideline 1 gave the most reliable guarantee for reduced impact.

The results show that the efficacy of these guidelines can be very dependent upon the specific product, its embodiment, and its interactions with the user and user habits. In the case of the kettle, all of the new guidelines proved helpful, and examples showed that they are applicable to other design scenarios. However, most guidelines are associated with environmental tradeoffs, and energy savings, for example, can be offset by high-embodied-energy or hazardous components.

4. CLOSURE

A systematic method is presented for extracting design for environment principles and guidelines from existing products. The method relies upon a combination of reverse engineering, green needs analysis, and life cycle assessment. Although the methodology was demonstrated for resource minimization, it can also be used to create guidelines in multiple areas of product utilization, such as durability and ease of disassembly. The resulting guidelines can be used to design future products, without repeating the methodology and the associated life cycle assessment. This advantage is particularly important for the early, conceptual stages of design.

When applied to a case study of electric kettles, the methodology successfully revealed four previously unpublished guidelines for resource efficiency during product use. Two of the guidelines improved performance more reliably when applied in tandem. It was shown that additional components can outweigh possible energy savings, and such tradeoffs must be carefully assessed.

An economic analysis, such as life cycle costing, could complement this environmental research method with additional insight. Life cycle costing (LCC) could provide additional economic support to design decisions. A few life cycle costing methods, using activity based LCC and combinations of LCA, design for environment and LCC, are outlined in the literature [27-30]. One additional question that could be answered by an economic analysis, besides justifying costs to the company, is: Do the energy savings of the electrical kettles justify the cost of the added components and functions? This issue is aligned with the marketability of the redesigned product. The proposed method would benefit from augmentation with market assessment tools, such as discrete choice methods [29, 30].

Future work lies in applying the method to other classes of products as well as other areas of green design. Designers are encouraged to insert additional techniques or steps depending upon their study needs and motivations. This process can result in interesting insights and adapted design tools, in addition to the desired new guidelines for green design. Two future activities that could further aid in development and proliferation of this method are concept generation studies based on the guidelines and industry trials of the method.

Acknowledgments

We gratefully acknowledge support from Dr. Phil Schmidt, Nathan Putnam, the University of Texas at Austin and members of the Webber Energy Group and the Product, Process, and Materials Design Lab at the University of Texas at Austin. Cassandra Telenko is supported by a National Science Foundation Graduate Research Fellowship.

References

[1] 1997, "ISO 14040:1997 Environmental Management - Life cycle assessment - Principles and Framework."

[2] Reap, J., Roman, F., Duncan, S., and Bras, B., 2008, "A Survey of Unresolved Problems in Life cycle Assessment Part 2: Impact Assessment and Interpretation," International Journal of Life Cycle Assessment, 13(4), pp. 374-388.

[3] Reap, J., Roman, F., Duncan, S., and Bras, B., 2008, "A Survey of Unresolved Problems in Life Cycle Assessment Part 1: Goal and Scope and Inventory Analysis," International Journal of Life Cycle Assessment, 13(3), pp. 290-300.

[4] Millet, D., Bistagnino, L., Lanzavecchia, C., Camous, R., and Poldma, T., 2007, "Does the potential of the use of LCA match the design team needs?," Journal Of Cleaner Production, 15(4), pp. 335-346.

[5] Fiksel, J., 1996, Design for Environment: Creating Eco-Efficient Products and Processes, McGraw-Hill.

[6] Telenko, C., Seepersad, C. C., and Webber, M. E., 2008, "A Compilation of Design for Environment Principles and Guidelines," ASME DETC Design for Manufacturing and the Lifecycle ConferenceBrooklyn, New York.

[7] Anastas, P. T., Anastas, P. T., and Zimmerman, J. B., 2007, "Design Through the 12 Principles of Green Engineering Design Through the 12 Principles of Green Engineering," Engineering Management Review, IEEE, 35(3), pp. 16-16.

[8] McDonough, W., Braungart, M., Anastas, P. T., and Zimmerman, J. B., 2003, "Applying the principles of green engineering to cradle-to-cradle design," Environmental Science & Technology, 37(23), pp. 434A-441A.

[9] Bras, B., and Baumeister, D., 2008, "Biologically Inspired Environmentally Benign Design and Manufacturing," NSF Engineering Research and Innovation ConferenceKnoxville, Tennessee.

[10] Raibeck, L., Reap, J., and Bras, B., 2008, "Life Cycle Inventory Study of Biologically Inspired Self-Cleaning Surfaces," ASME 2008 Inernational Design Engineering Technical Conferences and Conputers and Information in Engineering ConferenceBrooklyn, New York.

[11] Boothroyd, G., Dewhurst, P., and Knight, W., 2001, Product Design for Manufacture and Assembly, Marcel Dekker Inc., New York, New York.

[12] Keese, D. A., Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2007, "Empirically-Derived Principles for Designing Products with Flexibility for Future Evolution," ASME 2007 International Design Engineering Technical Conferences and Computers and Information in engineering ConferenceLas Vegas, Nevada.

[13] Palani Rajan, P. K., Van Wie, M., Campbell, M., Otto, K., and Wood, K., 2003, "Design for Flexibility - Measures and Guidelines," International Conference on Engineering DesignStockholm, Sweden.

[14] Crul, M., and Diehl, J., 2006, "Design for Sustainability: A Practical Approach for Developing Economies," http://www.d4s-de.org/ Accessed: May, 2009.

[15] Dowie, T., 1994, "Green Design," World Class Design to Manufacture, 1(4), pp. 32-38.

[16] Kriwet, A., Zussman, E., and Seliger, G., 1995, "Systematic integration of design-for-recycling into product design," International Journal of Production Economics, 38(1), pp. 15-22.

[17] Lewis, H., and Gertsakis, J., 2001, Design + Environment: A Global Guide to Designing Greener Goods, Greenleaf Publishing, Sheffield.

[18] Collado-Ruiz, D., Bastante-Ceca, M. J., Vinoles-Cebolla, R., and Capuz-Rizo, S. F., 2007, "Identification of Common Strategies for Different Electric and Electronic Equipment in Order to Optimize their End-of-Life," International Conference on Engineering DesignParis, France.

[19] Otto, K., and Wood, K., 2001, Product Design: Techniques in Reverse Engineering and New Product Development, Pearson Education, Inc., London.

[20] Otto, K. N., and Wood, K. L., 1998, "Product Evolution: A Reverse Engineering and Redesign Methodology," Research in Engineering Design(10), pp. 226-243.

[21] Pahl, G., and Beitz, W., 1999, Engineering Design: A Systematic Approach, Springer-Verlag, London.

[22] Hirtz, J., Stone, R. B., Szykman, S., McAdams, D. A., and Wood, K. L., 2002, "A Functional Basis for Engineering Design: Reconciling Evolving Previous Efforts," National Institute of Standards.

[23] Luttrop, C., and Lagerstedt, J., 2006, "EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development," Journal of Cleaner Production, 14, pp. 1396-1408.

[24] Hauser, J., and Clausing, D., 1988, "The House of Quality," Harvard Business Review, pp. 63-73.

[25] Goedkoop, M., De Schryver, A., and Oele, M., 2007, "SimaPro 7: Introduction to LCA."

[26] GaBi, "GaBi - Life Cycle Assessment (LCE/ LCA) software system for economic, ecological, and technical decision support in sustainable production and product design," http://www.gabi-software.com/ Accessed: May, 2009.

[27] Goedkoop, M., and Spriensma, R., 2001, "The Eco-Indicator 99: A Damange Oriented method for Life Cycle Impact Assessment - Methodology," Amsfoort, The Netherlands.

[28] Durfee, D. J., and Tomlinson, J. J., 2001, "Boston Washer Study," Department of Energy.

[29] Skerlos, S. J., Morrow, W. R., and Michalek, J. J., 2006, "Sustainable Design Engineering and Science: Selected Challenges and Case Studies," in Sustainability Science and Engineering, Volume 1: Defining Principles, M. Abraham, ed., Elsevier Science.

[30] Small, K. A., 2006, "Discrete Choice Demand Modeling for Decision-Based Design," in Decision Making in Engineering Design, K. E. Lewis, W. Chen, and L. C. Schmidt, eds., ASME, New York.