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Developing Green Design Guidelines:
A Formal Method and Case Study

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Developing Green Design Guidelines:

A Formal Method and Case Study

by

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Dedication

I dedicate this work to all the people who have given me opportunities to pursue my interests. I would like to dedicate it to my mother, Roseann, for teaching me how to pose questions and find answers. I would also like to dedicate it to my mother, my father, Peter, and my sister, Andrea, for always being proud and encouraging. Finally, I would also like to dedicate this thesis to my advisors, Dr. Seepersad and Dr. Webber, for guiding and supporting me in doing something new.

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Abstract

Developing New Green Design Guidelines:

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This thesis describes and demonstrates a method for consolidating, developing, and using green design guidelines for the innovation of greener products. Life cycle analysis (LCA) is one well-accepted tool for quantifying the environmental impacts of a product so designers can identify areas for redesign effort. However, LCA is a retrospective design tool that requires detailed design information that isn't known until designs are near completion. Alternatively, green design guidelines provide proven techniques for designing greener products. They can be used during the early stages of design, when many decisions fundamental to innovation and environmental impact are made and before LCA is viable. This thesis extends the work already done in green design guidelines, by updating the current knowledge base and introducing a method for

extending the set of existing guidelines to encompass new and emerging areas of sustainability.

While guidelines have been created from prior experience in design for environment and life cycle analysis, they have not been maintained as a shared and coordinated repertoire of green design solutions. Instead, sets of guidelines are scattered throughout the literature, contain overlaps, operate at different levels of abstraction, and have varying levels of completeness. For example, some areas of green design guidelines, such as design for disassembly, are well established, while other areas of green design guidelines, such as minimizing energy consumption during use, are still being explored. Additionally, while numerous examples of green design guidelines exist, many of the guidelines have no documented validation of their life cycle impacts.

The work for this thesis began with the compilation of a dynamic knowledge base of green design guidelines. This set of guidelines is a consolidation and updating of the green design guidelines already available in literature and can be used as a starting poinrt for future improvements and extensions as the field develops.

A standard method was then proposed and tested for creating guidelines in currently undeveloped areas of green design, particularly energy consumption during the operation of a product. The method employs reverse engineering techniques and life cycle analysis to identify green requirements and develop corresponding, new green design guidelines. A case study of electric kettles demonstrated the usefulness of the method by yielding four new guidelines and four, corresponding, energy saving re-designs. For this example, the redesigns showed that guidelines can reduce energy consumption, but may incur tradeoffs with other life cycle stages. Calculation of tradeoffs revealed a range of net life cycle impact values that were caused by increased manufacturing demands and variability in consumer use habits.

In addition to redesign in the kettle study, the four new guidelines were tested for usefulness in new product design by use of focus groups. Two groups were tasked with designing a new energy efficient toaster concept. Only one group was given the four green design guidelines that were uncovered using the proposed method. The design group using the new green design guidelines produced more viable and practical green features than the design group that did not have the guidelines as a design tool. These preliminary results suggest that the proposed method is useful for creating new guidelines that are beneficial to design teams tackling novel design problems that differ from the original case study. Further work is needed to establish the statistical significance of these results.

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Chapter 1: Introduction to Green Design Guidelines

Green design guidelines are historically proven techniques that designers can use to reduce the environmental impact of a product in one or more stages of its life cycle, ranging from material extraction to disposal of constituent parts. Green design guidelines are continuously being developed, but the process is not comprehensive or distributed uniformly across the different life cycles stages. Guidelines are often isolated with respect to a single stage of the life cycle, rather than existing as part of a complete set. Guidelines are also stated at inconsistent levels of detail, and created and validated using standards or methods that are undocumented. This thesis seeks to address these existing shortcomings in two ways: 1) by reconciling and collecting the bulk of design guidelines prominently available today, and 2) developing a method for creating further design guidelines by integrating life cycle analysis and reverse engineering. Case studies support this work by demonstrating the successful application of the method for creating guidelines and the usefulness of the resulting design guidelines for early stage, conceptual design of products.

1.1 Motivation

Companies want green design tools to help them meet increasing demand for more environmentally friendly products. Pressure from legislation and consumers make green design a competitive and necessary process for future products. Developed nations, such as the European Union, are developing new environmental legislation for products from electronics to automobiles. Major retailers, such as Wal-Mart, are also setting environmental design requirements. Finally, consumers are increasingly inclined to buy greener products. The complexity and growing number of green design requirements puts corporations and industrial designers in a position to benefit from more guidance in the form of guidelines and tools for measuring environmental performance.

Major legislation promoting green design in the United States includes product take-back legislation. Take-back legislation varies from state to state and is often the responsibility of the producer. Minnesota requires that manufacturers reclaim 90% of their electronics products. Manufacturers pay a yearly registration and recycling fee for each product sold within the state. They are reimbursed according to the number of reclaimed products [1]. Similar legislation calling for producer responsibility exists in a number of US states, and companies such as Dell, LG, Toshiba, Hewlett Packard, Sony, and others operate take-back programs [2]. Manufacturers use green design to make products that are more easily re-used and recycled to make product take-back more cost effective [3].

Legislation from the European Union directly requires environmental design. Two areas of legislation are most influential in supporting green design, the Restriction of Hazardous Substances (ROHS) and Waste Electrical and Electronic Equipment (WEEE) directives and the End of Life Vehicle (ELV) Directive [4, 5]. The WEEE and ROHS institute take-back legislation and lists of prohibited materials and reference guidelines for green design. The ELV directive requires that automotive manufactures recycle over 90% of their vehicles by weight. Both pieces of legislation will expand in the future and require companies to be pro-active with their green design initiatives.

Wal-Mart, the world's largest retailer, is preparing to meet the consumer trend towards increased environmental purchasing. Wal-Mart works with suppliers to create smaller, biodegradable, and reusable packaging. Recently, they announced environmental reporting requirements as well. Reusable laptop packaging is one example of green design supported by Wal-Mart's efforts [6]. As early as 2011, Wal-Mart will require that all of its 100,000 suppliers submit environmental reports for their products. Wal-Mart will then create an eco-label for its consumers [7]. This accountability provides a competitive edge for products if companies are able to assess and mitigate environmental impact.

As these legislative and consumer pressures increase, companies increasingly implement green design. Green design currently encompasses two major tools, life cycle analysis (LCA) and design for environment (DfE) guidelines. Life cycle analysis allows a company to measure the environmental impact of their products, but it is difficult to apply to concept generation when detailed product information is unavailable. DfE or green design guidelines are easier to use for creating more environmentally friendly production with less time and effort than required for LCA. Green design guidelines seem to be the most promising tool for early stage design and require further exploration. The following sections introduce the two tools and their uses in further detail.

1.2 LIFE CYCLE ANALYSIS

Life-cycle analysis is a standard quantitative tool defined by the ISO 14040 series for analyzing the environmental impacts of a product during all the stages of its life cycle [8].

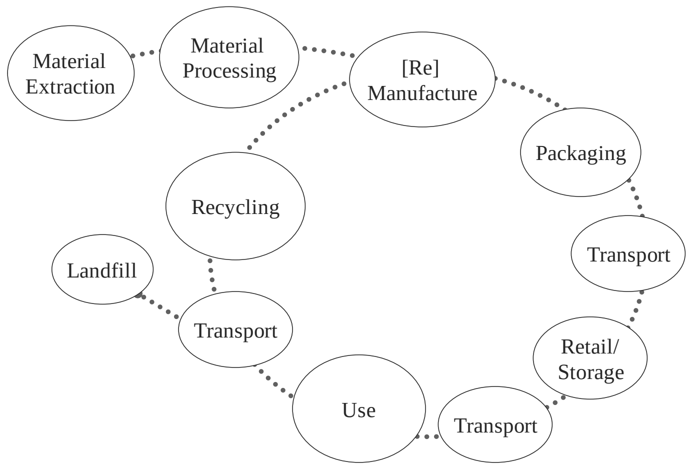


Figure 1-1: The Life Cycle Includes Processes from Material Extraction to Product Disposal

A complete life cycle analysis incorporates effects of life cycle stages, outlined in Figure 1-1, from extraction of raw materials, to production processes, to product usage, to end-of-life recycling or disposal of the product and its constituents. LCA requires an inventory of the specific inputs, such as raw materials and energy, and outputs such as air, land, and water emissions, for each life cycle stage. Figure 1-2 outlines an example inventory for a single process in the lifecycle.

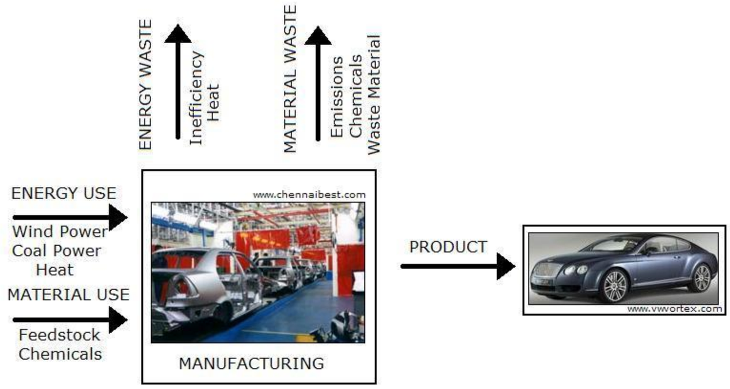


Figure 1-2: Analyzing a Single Life Cycle Process Requires Much Detail

The flows in an LCA are recorded as masses of specific substances, such as methane or gasoline. Each substance is assessed through modeling for its contribution to discrete types of environmental effect, called impact categories. Methane outputs contribute to global warming; the effect of all substances in this impact category are calculated on a global scale as global warming potential or equivalent tons of carbon dioxide. The process of life cycle analysis includes inventory for each unit process and assessment of environmental impact categories.

A complete life cycle analysis helps avoid, detect, and correct inadvertent transfer of harmful environmental impacts from one life cycle stage to another. For example, addition of a battery and a motor to create a hybrid vehicle reduces the environmental effects during the vehicle's useful life. However, an LCA reveals that environmental effects are increased in other stages of a hybrid vehicle's life cycle because of extra parts and toxic materials. Designers find LCA useful for quantitatively assessing the tradeoffs of product development decisions, but the time and data resources required for a complete and accurate LCA are often unavailable.

Environmentally conscious designers often replace unavailable LCA information with experience in order to balance life cycle tradeoffs. This experience can be LCAs of similar products or general notions of sustainability; its practical use has led to the creation of green design guidelines. The following paragraphs outline each life cycle stage and describe the types of design decisions and guidelines used for reducing environmental impact.

1.3 Designer Impacts on Life Cycle Stages

Material extraction and processing is the first stage of a product's life cycle. Materials come from sustainably cut forests, strained ecosystems, mines, recycling centers, and other sources, each with different environmental impacts. Many fundamental aspects of a product's function and form determine its environmental impact during material extraction and processing. For example, the material extraction of batteries differs from that of flywheels or ultra capacitors. An example of a product with reduced material extraction effects is paper made from Kenaf. Kenaf is a hibiscus plant that provides 3-5 times the amount of fiber per acre as southern pine and requires less water and pesticides. It assists in crop rotation and has a higher CO_2 absorption rate than trees. Kenaf pulp processing also uses less energy and fewer, less harmful chemicals. The end result is a whiter, cleaner, more durable paper product with lower impact on the environment [9].

Transportation effects are consequences of converting energy into motion, weight and number of shipments and choice of suppliers and markets. Transportation can be minimized between and within many stages of a product's life cycle. Using locally available materials is one way to reduce transportation impact. Weight and size of a product are two measurable design attributes that affect the necessary number of shipments and the load upon transportation vehicles, affecting emissions and fuel use. For example, Hewlett Packard introduced the HP Protect Messenger Bag to reduce the packaging and transportation effects of their HP Pavilion dv6929 notebook. Each notebook and its accessories are packed inside reusable messenger bags instead of separate foams, boxes and bags. The bags provide utility during shipment and style post retail. Each bag protects the notebook from drops of two feet. The smaller packaging facilitated a 31% increase in number of products per pallet delivered to retailers and a 25% decrease in the number of truck shipments [6].

Manufacturing and assembly stages of a product's life cycle have impacts related to facility maintenance, efficiency of chosen processes, materials and chemicals involved in those processes, and the cleanliness of facilities. A product's design can affect these by creating easily assembled structures and parts that are designed for targeted manufacturing processes to reduce defects and material waste. Sample product design challenges include creating a product using only one manufacturing process or only human assembly or by making use of material waste from other products or its own product line. For example, SolFocus CPV systems use optics and glass to concentrate solar power onto a small area of one square centimeter. Their design exhibits 25%

conversion efficiency of solar insolation to electrical power, with 0.1% of the photovoltaic material in a typical solar cell. The manufacturer claims that the design with glass instead of silicon uses high volume manufacturing techniques and yields the lowest carbon footprint of any solar technology [10].

Product retail affects the environment through packaging design and operation and climate control of storage. Food is one example of a product with high retail energy and facility needs [11]. Product packaging is created specifically for retail and becomes waste after purchase. Products designed to reduce retail effects might have shorter shelf lives, or be distributed from a central, low-maintenance facility by online shopping or not need housing at all and be transmitted via internet to in-home solid freeform fabrication machines.

During the product use stage, environmental impacts are incurred by operating energy, refilling consumables, cleaning chemicals, and other maintenance or operating processes. Products that aim to reduce environmental impact during the use stage embody new ways to meet customer needs with reduced resource requirements. Extending a product's useful life and maintaining its efficiency reduces the need for disposal and replacement of products. Products with long useful lives are often serviceable, upgradeable and resilient. Carefully specifying types and limiting amounts of energy and materials used by the product is also important to reducing environmental impact during the use stage. For example, Pax Scientific uses streamlining principles (e.g. the golden spiral) to create fluid machinery with minimal materials and lower energy requirements.

Their volute pump eliminates cavitation effects and uses 20-40% less energy than traditional centrifugal pumps [12].

The end-of-life stage of a product negatively affects the environment by disposing of re-usable materials, burning mixed media, or dumping solid waste. The selection of end-of-life alternatives is different for each of the materials and components in a product. The variety, types, and labeling of materials expedites more environmental processes, such as recycling or remanufacturing. A product that can be easily disassembled encourages recycling and remanufacturing. For example, Herman Miller has created multiple chair designs with end of life in mind. Their overall goal is to increase the lifespan of parts and materials by making it easier to disassemble the chair, recycle the pieces and refit pieces to new products [13].

1.4 The Importance of Early Stage Design Decisions

Although environmentally conscious design involves detailed design changes, like changing the material stock of paper or using higher recycled content, many designs with improved life-cycle impacts embody different concepts from their traditional counterparts. This statement is supported by examples from the previous section. Sol Focus uses lenses to focus light onto a substantially smaller photovoltaic area to increase efficiency and increase ease of manufacturing in comparison to traditional photovoltaic panels that, at best, track the sun. Hewlett Packard designers did not merely limit laptop-packaging material to the most important locations or change packaging materials to recycled or biodegradable materials. They recreated packaging as part of the product by making it a reusable messenger bag. These examples suggest that changes in the concept of a product often have more potential to improve life cycle impacts than changes in design details.

Most design decisions fundamental to environmental impact are set early in the design process, before life-cycle assessment is viable. These fundamental design decisions define a wider-range of environmental impacts and provide the most opportunities to make improvements. Figure 1-3 shows the perceived portions of environmental impact that are fixed with each stage of the design process.

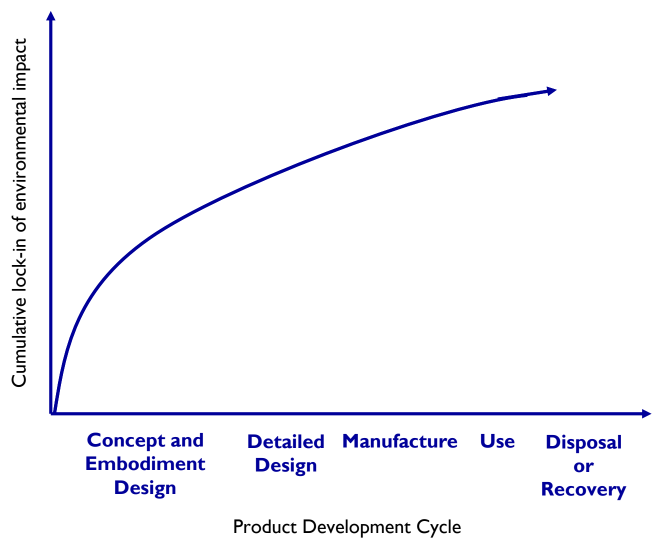


Figure 1-3: Environmental 'Lock-In' Over a Product’s Development [14]

From the evidence of these examples, one can conclude that green design should begin as early as possible in the design process. Early stage design tools are therefore needed to guide designers during the conceptual and embodiment stages of design.

Although LCA is a comprehensive analytical tool, it does not fulfill the need for an early stage design tool. Performing an LCA requires long lengths of time and highly detailed data describing the final product. For example, LCA requires complete information on the mass of each type of material in the final product, and precise quantities of material and energy inputs and outputs of each stage of the production process. This inventory information is typically available only in the final stages of product development, after most design decisions have been made. Figure 1-4 depicts a flowchart of a typical design process and outcomes of each design stage.

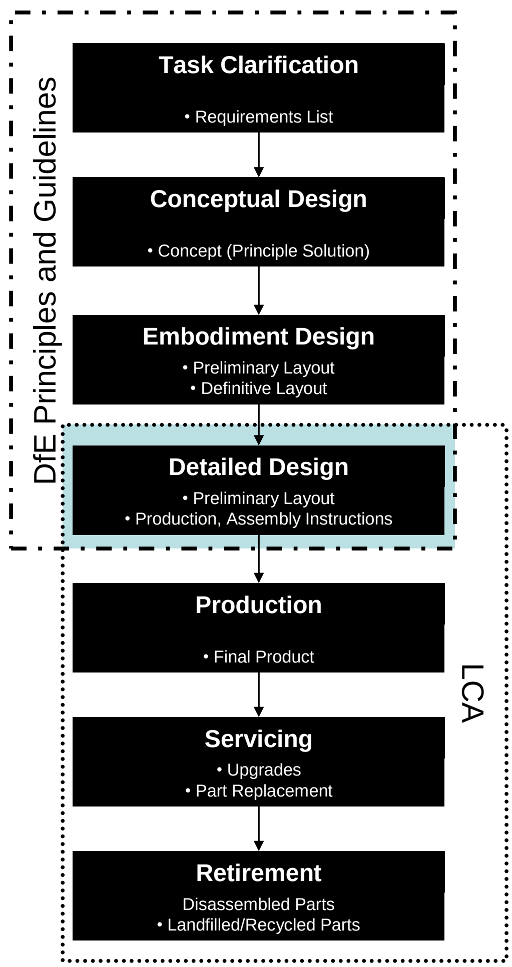


Figure 1-4: LCA is a Retrospective Tool in the Design Process, while DfE Principles are a Concurrent Design Tool, adapted from Pahl and Beitz [15]

LCA and Design for Environment (DfE) principles and guidelines are shown alongside the design stages during which they can be applied. LCA requires detailed information that is available only towards the end of detail design and the beginning of product manufacturing. LCA can therefore be called a retrospective design tool, because it is limited to post-evaluation, product comparison, and conservative redesign or augmentation of bills of materials.

1.5 Green Design Guidelines as a Concurrent Design Tool

DfE principles and guidelines have been developed to guide designers in creating product concepts and layouts when lack of time and detailed information prohibit a full LCA [16]. Examples of guidelines include "ensuring rapid warm up and power down" for energy efficiency and "ensuring easy access to fasteners and joints" for disassembly and recycling. DfE principles often reflect lessons learned from LCA. Products have been analyzed with LCA tools or lifecycle stage specific tools to correlate design decisions with environmental performance. Guidelines generalize flaws or improvements based on comparing designs before and after environmental or other resource analysis. However, the existing literature does not usually present a full LCA examining the tradeoffs of guidelines.

DfE principles and guidelines also promote consistency and systematization between design processes, facilitate communication of new discoveries, and provide an important set of environmental solutions and problems to complement or replace unavailable LCA data [16]. As a set, guidelines encompass most life cycle stages and can be used to anticipate tradeoffs between life cycle decisions. However, the existing literature does not systematically update or evaluate an existing reference set of guidelines.

1.6 Research Objectives and Approach

The potential of green design guidelines is hindered by a lack of validation, documentation, and systematic development. A dynamic set of green design guidelines, backed by life cycle analysis data, can be an effective, green design tool during the initial stages of product design. While guidelines are presented as a design tools, they have yet to be unified as a single, comprehensive design tool. Many guidelines are not verified, and the breadth of guidelines is expanding. These research needs are the subject of this thesis, which focuses on answering the following three research questions:

> Research Question #1:*What guidelines currently exist and how can these be reconciled into a single set or body of knowledge?*
>
> Research Question #2: *How can new guidelines be developed in a standard, rigorous and transparent way?*
>
> Research Question #3: *What effect will these guidelines have on the life cycle impacts of new products?*

The first research question addresses the non-uniform development of DfE in the previous three decades. Review of publications from 14 research groups, yielded over 100 different principles and guidelines with inconsistencies as well as some overlaps in form and subject. The guidelines were categorized into two levels: first, principles and, second, guidelines for achieving the principles. Guidelines were then reconciled into a smaller set of principles and guidelines. Overlaps and disparities in detail, focus, or phrasing were resolved by following four main criteria for what makes guidelines helpful to designers. These criteria were deduced from the strengths of current green guidelines. The resulting set of guidelines from the literature focused on material choice, recycling, and end-of-life. Other areas, such as energy efficiency, are still being developed. This set of green design guidelines is not considered exhaustive and documentation of the development and validation of many of the guidelines was not found. Each principle generally focuses upon the effects of one stage of a product's life cycle, but a designer should be aware of when a guideline improves or possibly worsens environmental impact in all stages of the life cycle. The need for more, validated guidelines motivated the second research question to devise a method for expanding the current set of guidelines.

For manageability, it seemed that a method for developing guidelines should focus on developing guidelines under one principle at a time, but should also consider other principles by including an LCA and tradeoff analysis to understand the broader effects of each guideline. Each principle generally focuses upon the effects of one stage of a product's life cycle, but a designer should be aware of when a guideline improves or possibly worsens environmental impact in all stages of the life cycle. The principle selected for study in answering research question #2 was design for energy efficiency and reduction during the use stage of the life cycle. Because this area of guidelines is under-developed and can incur tradeoffs between energy impacts and material, toxicity or manufacturing effects, energy efficiency during use provides a relevant and multi-faceted case study for creating guidelines.

The method integrates environmental design and analysis with a systematic reverse engineering approach. It combines general tools, such as customer needs analysis and black box modeling, with environmental tools, such as environmental requirements and lifecycle analysis. Environmental requirements are used to target green design goals that motivate each step of the process. The process considers multiple benchmark products and aims to create guidelines for future product design without requiring extensive experimentation and lifecycle assessment.

A case study tested the method by comparing three competing electric kettles. The method with reverse engineering, environmental requirements and LCA helped develop and examine four new guidelines. The four new guidelines reduced the effects of energy used by the kettles, but led to tradeoffs when their embodiment required manufacturing of additional components. The third and final research question asks for an evaluation of the usefulness of the guidelines for achieving the ultimate goal of this research, reducing environmental impact in future design problems.

A concept generation case study helped verify that the new guidelines can help a designer create greener concepts. A problem statement was created for the design of an energy saving toaster. A toaster was chosen because it performs a similar function to electric kettles, is also power intensive and contains simple components. The problem statement was given to two groups of six designers each, one with guidelines and one without. Useful features within each groups' set of concepts were counted to estimate how effective the guidelines were and what further research needs to be done to ensure that guidelines are effective.

1.7 Thesis Organization

Existing green design guidelines are reconciled and compiled in the second chapter of this thesis. The third and fourth chapters provide the method and example case study for expanding the set of existing green design guidelines while the fifth chapter describes the case study of concept generation to evaluate the usefulness of the guidelines. A final, sixth chapter, details the contributions of this thesis and existing future work.

Chapter Two: A Reconciled Set of Guidelines reviews the previous sets of green design guidelines, design for environment guidelines, and design for sustainability guidelines. Four criteria for formulating guidelines useful to designers were distilled from reviewing the literature. The guidelines taken from the literature were mapped and reconciled to meet the criteria and avoid overlap. This review of the literature revealed needs for keeping a central set of design for environment guidelines as well as further development of guidelines in certain stages of the life cycle and further validation and study of the effects of using guidelines.

Chapter Three: A Method for Identifying and Validating Guidelines shows that no standard method for creating guidelines with a life cycle basis has been established by prior work. The method provides a framework and procedure for developing guidelines using common tools and needs analysis and life cycle assessment.

Chapter Four: Case Study in Discovering New Green Design Guidelines demonstrates the method from Chapter 3 as successfully applied to electric kettles. During the process, four new guidelines were discovered and common tools were applied in new ways to reduce the environmental impacts of the benchmark product.

Chapter Five: Evaluating the Usefulness of New Guidelines takes the guidelines that were produced from the case study in Chapter 4 and investigates how they can be used to improve concept generation. New energy efficient toaster concepts generated by a control group of five participants without knowledge of the new guidelines were compared to concepts generated by a green design group of five participants with knowledge of four new guidelines.

Chapter Six: Contributions and Future Work reviews the main findings of this research and compares these to prior knowledge in the field of green design. Numerous possibilities for further work and new research stemming from the findings of this thesis are also discussed.

Chapter 2: Reconciling and Compiling Green Design Guidelines

Designs for environment (DFE) guidelines communicate decades of experience in designing for all stages the life cycle. They originally focused on pollution and recycling, but have recently expanded to include energy and water. Each guideline is created to lessen environmental impact in one aspect of a product's life cycle. Therefore, addressing *all* lifecycle impacts usually requires multiple design guidelines. If designers are made aware of all of the guidelines, they should be better equipped to avoid or manage tradeoffs between life stages.

The difficulty with DfE principles and guidelines is that they are scattered throughout the literature, in various forms and levels of abstraction, and with uneven emphases on specific life-cycle stages, products, or industries. A comprehensive set of DfE principles is needed that synthesizes best practices from across these various sources, organized in a form that is useful to designers in a broad range of industries. This need is addressed in this chapter; An organizational tool, called a mind-map, and four criteria were used to create a comprehensive set of the current DfE principles and guidelines. The resulting set of green design guidelines is presented in this chapter and Appendix A. It is targeted for use by designers who wish to improve life-cycle impact.

2.1 EXISTING GREEN DESIGN GUIDELINES

Many published lists of DfE principles focus on a single life-cycle stage, often in the form of Design for X strategies [14, 16-19]. Examples include Design for Disassembly, Design for Recycling, and Design for Energy Efficiency. End-of-life strategies, such as

Recycling and Disassembly, are relatively well established in the literature while principles for energy efficiency are still being developed. Because these types of principles and guidelines have been developed and published separately, the risk is that the designer may focus on a few simple strategies and lose the holistic, life-cycle perspective provided by a more comprehensive set of principles.

Many industries and companies have developed their own sets of specific guidelines, rules, and checklists that may restrict the design space[20-22]. Volvo, for example, instituted a Black, Grey, and White list of prohibited, cautionary, and clean materials in the late 80s/early 1990s [23]. Likewise, Siemens created its own list of 40 principles [24]. As an explicit example, Hewlett Packard's mobile products follow rules that are specific to electronic displays, such as "Set display brightness to lowest comfort level to conserve energy / battery life [25]." Because the rule is product-specific, it confines the designer to a specific technology, such as electronic displays, rather than alternatives, such as organic displays that reflect ambient light. A more general principle—applicable to a broader range of products—could encourage designers to specify the best-in-class energy efficiency technology, and reevaluate it every design cycle. This example illustrates the difficulty with industry- or product-specific guidelines and shows that principles may be more useful if they apply to a range of products.

Similarly, many varied regulations are being developed for products in different regions and industries. The Restriction of Hazardous Substances (ROHS) and Waste Electrical and Electronic Equipment (WEEE) directives are two widely accepted sets of rules for prohibited materials in electronics [5]. The European Eco-Label [26] provides a few product specific guidelines and requires a full life-cycle assessment. The McDonough Braungart Design Chemistry Certification [27] offers a checklist and point system to certify different levels of products, most of which are in the area of materials and chemicals. While these are useful requirements for a designer to meet, they do not provide the range of guidance that sets of DfE principles offer.

In contrast to the industry- and product-specific sets of guidelines, some sets of DfE principles are extremely abstract. These lists typically articulate high-level goals for creating ecologically beneficial products. Anastas *et al.* and McDonough *et al.* provide lists of abstract principles [28-30], such as "it is better to prevent waste than to treat or clean up waste after it is formed." Luttrop *et al.* created a list of ten generic principles that bring DfE to an intermediate level from which each product designer derives a set of specialized guidelines [31]. Although these lists cover the entire scope of the design process as shown in Figure 1-4, they do not provide actionable guidelines for improving a product and inspiring innovation. How these principles might be embodied in a product is not apparent.

Finally, many DfE strategies are focused on managers or manufacturing process specialists, rather than product designers. Over 100 guidelines have been established by combining DfE for product, packaging, process and management with a focus on how DfE strategies work in cooperation across companies [14, 17-19, 32]. Referring back to Figure 1-4, these lists extend DfE guidelines past design to include everything from corporate attitude to the housekeeping of processing plants. Overemphasizing the holism of DFE, many guidelines within these lists become irrelevant to the product designer.

Companies should assume an environmental management system (EMS) and designers should acquire knowledge of production processes and supply chains [33], but design guidelines should describe design decisions. For example, a designer does not need a principle for good housekeeping but a guideline as to how good housekeeping is facilitated by the design of the product (e.g. environmental Design for Manufacturing.)

While general principles, DfX guidelines, and product specific checklists do exist, designers are left to sift through these sources to create their own version of DfE. A consolidated set of principles does not exist for the general product designer. The following section details the process used to create such a comprehensive set of principles from these diverse resources.

2.2 METHOD FOR COMPILING GUIDELINES FROM MULTIPLE SOURCES

The principles, guidelines, and checklists described in the previous section were reconciled to create a uniform design tool for early stage design decisions. The various types and levels of guidelines were organized and synthesized into categories of decisions and levels of abstraction using a mind-map. Mind-maps are tools for organizing solutions to design problems [34]. To address inconsistencies within the current literature, we established a set of four criteria that each of our final principles and guidelines should meet, defined as follows:

- Designer-oriented: the principle must be within the scope of a product designer
- Actionable: the principle must propose an avenue for improving the design
- General: the principle must apply to a large range of products

- Positive Imperative: the principle must focus on creating the best solution possible

During consolidation, each principle was revised to meet the four criteria. In this section, the four criteria are described in detail. A summary follows of the mind-mapping technique and consolidation process.

The **designer-oriented** criterion defines the audience for this set of principles and guidelines. It requires that each principle be formulated to direct designers, rather than managers or other stakeholders. When reformulating principles to be more designer-oriented, we found it helpful to refer to Pahl and Beitz's list of the types of decisions typically made by a product designer: 1) overall layout, 2) form and types of components, 3) selection of materials, and 4) communication with the user or manufacturer [15].

The **actionable** criterion requires that high-level goals, such as "Ensure long life," be broken into potential avenues for achieving the goal. Actionable avenues for ensuring long life might be ensuring "that aesthetic life meets technical life" or planning "for efficiency improvements." The purpose is to ensure that designers are left with not just high-level aspirations, but ideas of discrete design improvements. The final set of principles includes high-level principles (goals) and supporting guidelines (avenues). Accordingly, designers are motivated by the abstract goal or principle, "ensure long life" for example, and simultaneously presented with corresponding guidelines that offer design avenues a designer may not have traditionally considered when following a more abstract principle.

The **general** criterion requires that a principle applies to a variety of product categories and design problems. For example, directions for using natural materials, or not using synthetic or non-ferrous metals, were generalized to terms such as renewable, recyclable, and low-embodied energy. As an example of an industry-specific rule, furniture designers are encouraged to specify sustainably-forested wood [14, 21]. This rule was considered under the more general guideline, “Specifying renewable materials.”

Using the **positive imperative** form helps focus the designer on best practices, what to use rather than what not to use. Many current design guidelines are of the form: “Do not use…” or “Avoid… toxic or hazardous substances [18].” A slight modification of the guideline: “Specifying non-hazardous and otherwise environmentally “clean” substances, especially in regards to user health” [14, 17-19, 32, 34-38] places immediate focus on safer materials instead of materials with unknown safety. With the principle “Ensure healthy inputs and outputs by” [28, 31] at the front, it becomes the positive imperative form.

These criteria were applied in the context of a mind-mapping process [34] for categorizing and synthesizing the principles gathered from the literature. A mind map is a visual recording of a brainstorming session. The center of a mind map contains the overall function or goal of the brainstorming session. Ideas and possible solutions are drawn from the center and grouped into sets of similar concepts. For the purposes of this research, “Design for Environment” was placed as the overall objective at the center of the mindmap, and principles, guidelines, and rules fulfilling this objective were placed as sub-branches. Principles were the level directly stemming from DfE. Guidelines stemmed from unique principles and rules stemmed from guidelines. Figure 2-1 presents a portion of the final mind map as an example. Use of the mind-mapping technique for sorting existing guidelines helped highlight interdependencies and overlapping principles and arrange the principles into hierarchical levels of abstraction.

The initial mind-map yielded four levels of principles branching from the DfE center. The first level contained principles. The second level contained either further sub-principles or guidelines. The third level contained either rules stemming from guidelines or guidelines stemming from sub-principles. The lowest level consisted of product specific rules. These four levels were then reconciled into the two desired levels of abstraction, principles and guidelines.

Equivalent guidelines were combined into single encompassing guidelines, and all principles and guidelines were reviewed to meet the four criteria: designer-oriented, actionable, general, and positive imperative. For example, "Incorporate lightweight moving components" [34] and "Minimize volume of heated components" [39] were combined into one, more general guideline, "Minimizing the volume and weight of parts and materials to which energy is transferred." Another guideline, "use calibration marks on the product so that the user knows exactly how much auxiliary material… to use" [40] was made more general, but still actionable, by changing the specification of calibration marks to feedback mechanisms in general, "using feedback mechanisms to indicate how much energy or material is being consumed." The methodology resulted in 6 principles and 65 guidelines. Select guidelines are discussed in this Chapter and all of the guidelines are explained in Appendix A.

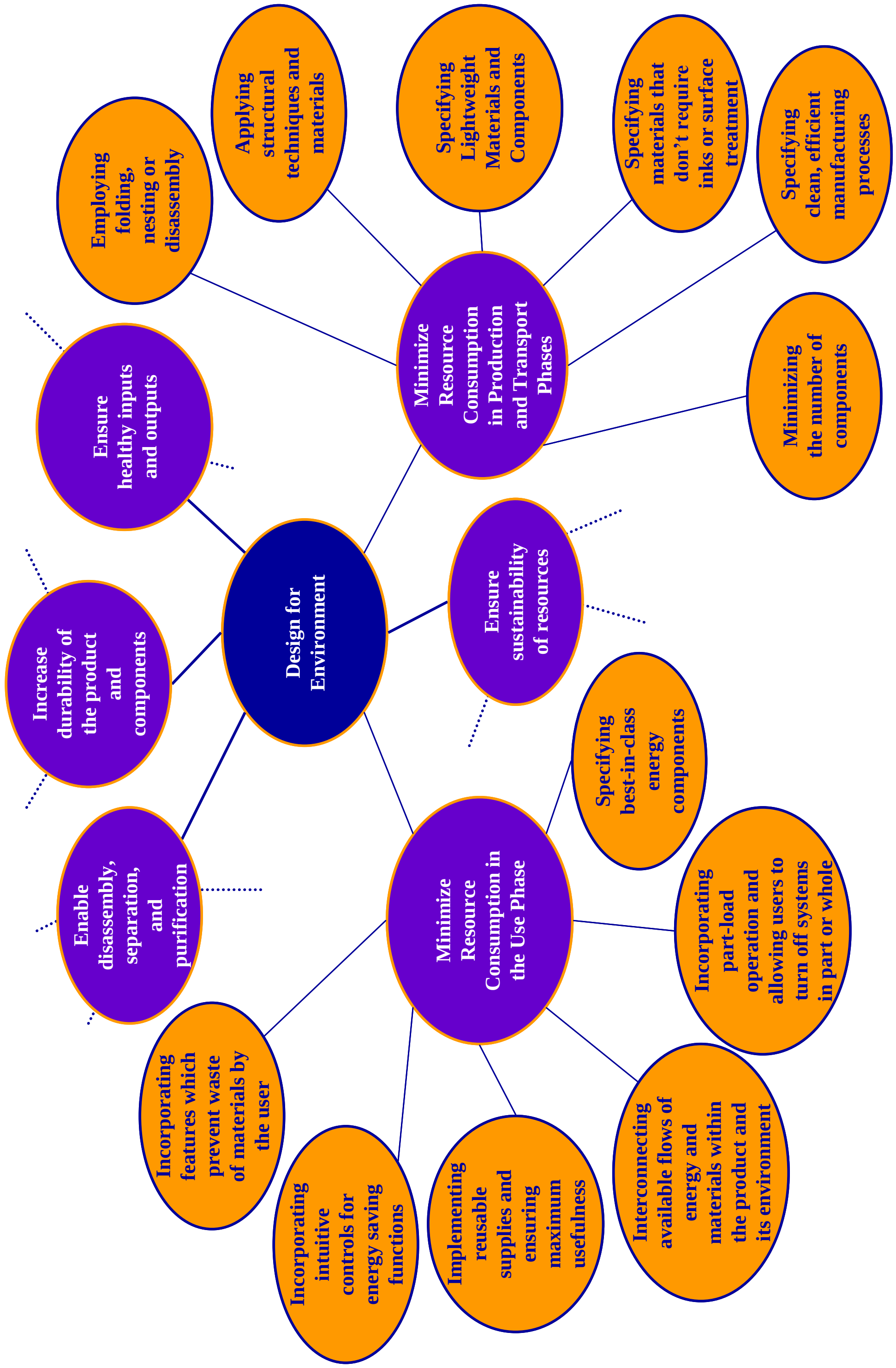


Figure 2-1: Final DfE Mind Map (abridged)

2.3 DESIGN FOR ENVIRONMENT PRINCIPLES

This section presents the full compilation of principles with select examples of products. Distinctive to this work are the arrangement using principles and supporting guidelines as well as the wording of each principle and guideline. The principles come from the mind map and literature review. They are made to fit the criteria and are separated as follows: principles A and B for resource selection, C for production and transportation, D for use, E for extended life and F for disassembly. Each principle is followed by guidelines for making design decisions that support the principle's goal. Select examples are used in this chapter to demonstrate how guidelines might be applied and how some guidelines can be combined. The full set of guidelines with descriptions appears in Appendix A.

2.3.1 Principle A: Ensure Sustainability of Resources

Guidelines for fulfilling principle A, "Ensure sustainability of resources by…", are shown in Table **2-1**. Principle A addresses resource depletion by encouraging use of resources that can replenish at rates higher than their consumption and reuse of resources that cannot replenish, such as metals, toxic materials, and components. The guidelines apply to every aspect of the product, including energy, parts, consumables and packaging.

Table 2-1: Principle A - Sustainable Resources

A. Ensure sustainability of resources by: [14, 19, 28] 1. Specifying renewable and abundant resources [14, 15, 17, 18, 32] 2. Specifying recyclable, or recycled materials, especially those within the company or for which a market exists or needs to be stimulated [14, 16-19, 24, 32, 34-38] 3. Layering recycled and virgin material where virgin material is necessary [17, 32] 4. Exploiting unique properties of recycled materials [17, 32] 5. Employing common and remanufactured components across models [16-18, 24, 34, 38] 6. Specifying mutually compatible materials and fasteners for recycling [15-18, 24, 32, 34-38] 7. Specifying one type of material for the product and its subassemblies [16, 17, 19, 24, 31, 32, 34, 35, 37, 38, 41]

Guideline A-4: Exploiting unique properties of recycled materials.

Guideline A-4 from the set above reminds designers to utilize the qualities of recycled materials. Treatment of materials, such as forming and pigmenting, adds extra and potentially harmful processing steps. By making use of existing textures, color combinations, and intermixed patterns of recycled material, a designer can realize untapped potential, forgo additional production steps, and divert valuable material from landfills.

Bitters Co. offers an example of a product that reuses material, taking advantage of the material's existing characteristics. They design doormats and key-chains using foam rubber salvaged from the excess material of Flip Flop production. Re-using waste from the manufacturing stage, Bitters Co. maintains the original coloring to create patterns in their final doormat or key-chain. Figure 2-2 shows floating key chains made from the rubber foam [42].

Figure 2-2: Bitters Co. uses the Original Properties of Flip Flop Scraps to Make New Products [42]

Guideline A-5: Employing common and remanufactured components across models.

Guideline A-5 is a product class or product line approach to guideline A-2 (Specifying recyclable materials…) There is no advantage to designing for recyclability, durability, or reuse if the parts are not reused or become outdated. By specifying common parts and remanufactured components, a designer ensures that those parts have a market. Re-used parts have longer useful lifetimes and avoid the unnecessary materials and manufacturing associated with virgin components in new products.

Rank-Xerox® photocopiers are examples of designing with remanufactured components [34]. Designers overhauled the structure and modularity of their photocopiers to accommodate remanufactured modules from current and previously introduced products. Comparing the products in Figure 2-3 reveals that the Document Centre™ 440 only makes additions and a few component replacements to the previous Document Centre™ 220 model. Each model contains remanufactured parts, such as paper trays, and common cartridges [43].

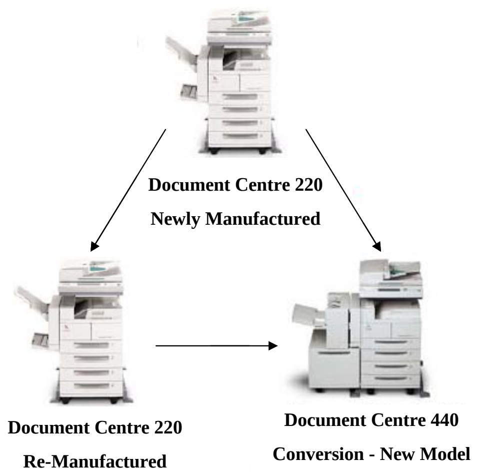


Figure 2-3: Xerox® Saves Resources by Designing With Remanufactured Components and Modules Since the 1990s [44]

2.3.2 Principle B: Ensure Healthy Inputs and Outputs

Table 2-2 lists guidelines for fulfilling principle B, "Ensure healthy inputs and outputs by…" Healthy inputs and outputs are those that do not cause environmental degradation or adversely affect human health and instead provide nutrients or return other benefits to the environment. This principle requires elimination of hazardous substances and pollutants as well as the conversion of waste to useful environmental nutrients. As with principle A, principle B applies to every aspect of the product, including consumables, and packaging.

Table 2-2: Principle B - Cleaner Resources

B. Ensure healthy inputs and outputs by: [28, 31] 8. Installing protection against release of pollutants and hazardous substances [17, 32] 9. Specifying non-hazardous and otherwise environmentally "clean" substances, especially in regards to user health [14, 17-19, 32, 34-38] 10. Ensuring that wastes are water-based or biodegradable [14, 16, 24, 37] 11. Specifying the cleanest source of energy [14, 17, 32, 34] 12. Including labels and instructions for safe handling of toxic materials [17-19, 34, 36-38, 41] 13. Specifying clean production processes for the product and in selection of components [17, 24, 36, 37] 14. Concentrating toxic elements for easy removal and treatment [17, 31, 32, 36, 37] [41]

Guideline B-11: Specifying the cleanest source of energy.

Guideline B-11 focuses on emissions and waste from energy sources. Often, a large portion of a product's environmental impact is dependent upon the type of energy specified during use. By using non-burning, energy sources, such as solar and wind power, a product can avoid effects of pollutants and solid waste. This guideline applies to energy storage as an additional form of energy source; one would choose rechargeable batteries over disposable batteries when following this guideline. The disposal of one set of rechargeable batteries correlates to dozens of single-use batteries, thereby reducing toxic waste.

The Seiko Kinetic® Auto Relay, shown in Figure 2-4 exhibits both energy storage and primary energy aspects of principle B; it has no batteries and no external chargers. Seiko's watch is powered by the kinetic energy of the wearer's movement, a readily available and clean energy source. The watch is charged after a few side to side motions, and operated by an automatic power generator [45]. Driving power for the clock hands halts after the watch is stationary for 72 hours. The watch can maintain the correct time internally for up to 4 years of inaction. Within those four years, the watch can be picked up and shaken to return to the correct time [46].

Figure 2-4: Kinetic Energy Powers the Seiko Kinetic® Auto Relay [46]

2.3.3 Principle C: Ensure Minimal Use of Resources in Production and Transportation Phases

Principle C, "Ensure minimum use of resources in production and transportation phases…" encourages the designer to think about how product attributes affect the efficiencies of the manufacturing process and transportation. Guidelines for fulfilling principle C, shown in Table 2-3, provide direction in structuring and sizing products to reduce material waste in production and reduce the load and number of shipments as a means of lowering fuel use and emissions.

Table 2-3: Principle C - Production and Transport

C. Ensure minimum use of resources in production and transportation phases by: [31, 38] 15. Replacing the functions and appeals of packaging through the product's design [17, 32] 16. Employing folding, nesting or disassembly to distribute products in a compact state [17, 32] 17. Applying structural techniques and materials to minimize the total volume of material [14-19, 24, 31, 32, 35-38] 18. Specifying lightweight materials and components [16, 18, 24, 32] 19. Specifying materials that do not require additional surface treatment or inks [14, 17, 32] 20. Structuring the product to avoid rejects and minimize material waste in production [15, 17, 24, 32] 21. Minimizing the number of components [17, 24, 32, 34] 22. Specifying materials with low-intensity production and agriculture [18, 32] 23. Specifying clean, high-efficiency production processes [14, 18, 24, 32, 37] 24. Employing as few manufacturing steps as possible [37]

Guideline C-17: Applying structural techniques and materials to minimize the total volume of material.

Guideline C-17 challenges the designer to optimize the structure of their housing and components rather than over-dimensioning their product. Rather than increasing thickness or size to meet structural requirements, one should use sturdier and more compact geometries and specify lightweight and high strength materials. Figure 2-5 shows the Black and Decker® Leaf Hog™ which uses ribbing to reduce part thickness and achieve structural rigidity and support for components.

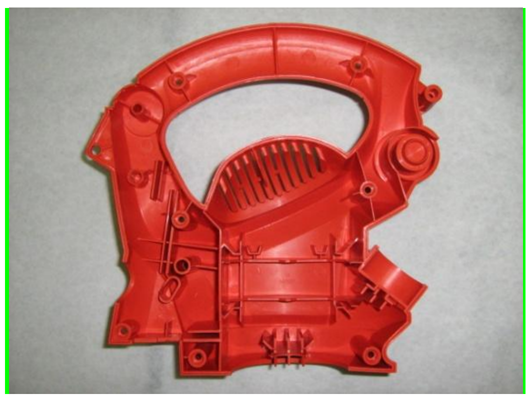


Figure 2-5: The Black and Decker® Leaf Hog™ Uses a Ribbed Structure to Increase Strength and Lower Weight and Material Use

2.3.4 Principle D: Ensure Minimal Use of Resources during Use

Principle D, "Ensure minimum use of resources during use by…", asks designers to create products that are more efficient and eliminate consumable features. Using the guidelines, designers can create products that meet performance requirements without wasting energy or materials. These guidelines help designers improve consumer actions and eliminate sources of waste. The guidelines for principle D are shown in Table 2-4.

Table 2-4: Principle D - Use Phase

D. Ensure efficiency of resources during use by: [14, 19, 28]
25. Implementing reusable supplies or ensuring the maximum usefulness of consumables [14, 17, 20, 24, 32]
26. Implementing fail safes against heat and material loss [17, 20, 32, 34, 36]
27. Minimizing the volume, area and weight of parts and materials to which energy is transferred [17, 20, 32, 34]
28. Specifying best-in-class energy efficiency components [17, 18, 20, 32, 34, 36]
29. Implementing default power down for subsystems that are not in use [14, 17, 32, 34]
30. Ensuring rapid warm up and power down [20]
31. Maximizing system efficiency for an entire range of real world conditions [19, 20, 32]
32. Interconnecting available flows of energy and materials within the product or between the product and its environment [19, 28]
33. Incorporating part-load operation and permit users to turn off systems in part or whole [17, 19, 32, 34]
34. Use feedback mechanisms to indicate how much resource is being consumed [14, 18]
35. Incorporating intuitive controls for resource-saving features [18, 20]
36. Incorporating features that prevent waste of materials by the user [17, 32]
37. Defaulting mechanisms to automatically reset the product to its most efficient setting [17]

Guideline D-36: Incorporating features that prevent waste of materials by the user.

Guideline D-36 requires designers to be more conscious of how their product will be used or misused, and what aspects of material use can be guided by design. A few examples of this guideline are found in products that use calibration marks for a user to measure the minimal amount of water, washing powder, coffee, or other consumable resource [17, 32]. A funnel that prevents spillage is another tool for preventing waste [17, 32].

An example of this guideline in the use phase would be the ECO kettle™, shown in Figure 2-6. Electric kettles provide better insulation and direction of heat (D-26) using an enclosed heating coil. Additionally, the ECO kettle™ accounts for a common mistake of water-heating consumers – heating too much water.

Figure 2-6: The ECO Kettle™ Helps Users Heat Only What They Need [47]

Combining D-36 with D-27 (minimizing the volume of heated areas), the designers separated the kettle into storage and heating compartments, each have gradations for measuring waste. Most importantly, the storage compartment allows the user to continue their habit of leaving extra water in the kettle while simultaneously beginning a habit of heating the correct amount of water. Thus, energy is saved and environmentally responsible habits are facilitated.

Guideline D-32: Interconnecting available flows of energy and materials within the product and its environment.

Guideline D-32 exhibits a core principle of sustainability--imitating nature by turning nearby waste material and energy into primary resources. Some examples of turning ambient and waste energy into usable power are solar power and regenerative braking. Solar power makes use of the prime source of energy available to the planet, but requires the designer to be mindful of product exposure to sunlight. Regenerative braking reverses the electric motor to recapture vehicle momentum while simultaneously braking.

Retrofit products, such as the SinkPositive in Figure 2-7, are now being marketed to the environmentally conscious consumer to achieve this guideline. One flush of a toilet sends one gallon or more of potable water down the drain. Washing one's hands after using the toilet causes additional loss of this increasingly important commodity. SinkPositive combines the two interlinked functions by connecting a sink to your toilet tank. After a user flushes the toilet, replacement water is fed through an added faucet, providing water to the patron at just the right moment and cutting out the additional water use needed to wash hands in a separate toilet and sink bathroom.

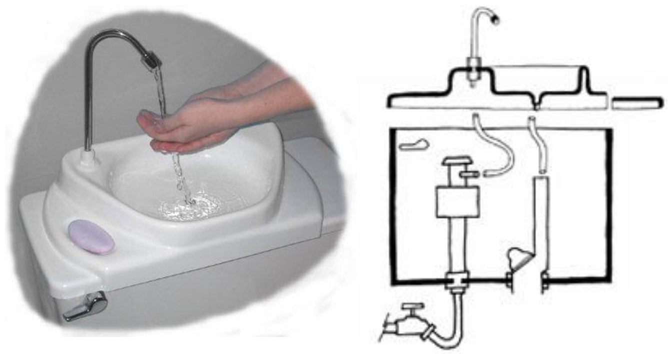


Figure 2-7: SinkPositive Diverts Tank Water Through a Faucet [48]

2.3.5 Principle E: Ensure Appropriate Durability of the Product and Components

Extending the life of a product avoids transportation and processing steps of creating a new product, as well as postponing waste, recycling, and remanufacturing steps of the current product. Principle E addresses this aspect by presenting two important strategies for durability: creating durable and resilient structures and components as well as enabling the product to be maintained, updated and refurbished. In this way, old, inefficient technology is not prolonged. Conversely, ensuring durability of a product that can be updated in parts gives designers the time for development of new, innovative, environmental solutions for the next generation of product

.

Table 2-5: Principle E - Durability

E. Ensure appropriate durability of the product and components by: [14, 24, 28, 31, 36]
38. Reutilizing high-embedded energy components [28]
39. Planning for on-going efficiency improvements [19, 36]
40. Improving aesthetics and functionality to ensure the aesthetic life is equal to the technical life [14, 17, 32, 36, 37]
41. Ensuring minimal maintenance and minimizing failure modes in the product and its components [16-19, 37, 38]
42. Specifying better materials, surface treatments, or structural arrangements to protect products from dirt, corrosion, and wear [15, 31]
43. Indicating on the product which parts are to be cleaned/maintained in a specific way [17, 32]
44. Making wear detectable [15, 17, 32]
45. Allowing easy repair and upgrading, especially for components that experience rapid change [15, 31]
46. Requiring few service and inspection tools [15]
47. Facilitating testing of components [15]
48. Allowing for repetitive dis- and re- assembly[15]

Guideline E-45: Allowing easy repair and upgrading, especially for components that experience rapid change.

Guideline E-45 tries to avoid the waste problem that many consumers experience: a product contains many components and features, then one of those becomes obsolete or breaks down and the consumer is forced to purchase an entirely new product. This situation is not only upsetting and expensive for some consumers, but creates an unnecessary amount of waste, rendering operational components useless. Evidence of this phenomenon is most apparent in the electronics industry, where cell phones are replaced yearly. If designs allow for easy replacement, access and repair of electronic components that fail or become obsolete, the operating components can continue their useful lives.

The modifiable desktop computer exemplifies this guideline. Every tower has standard slots and sizes for DVD ROMs, CD ROMs, and video cards. Motherboards come with similar slots, with options to upgrade and change memory types. Whole computers can be built at home from spare parts – saving assembly energy, reducing waste of old parts, and allowing upgrades to more energy efficient components.

2.3.6 Principle F: Enable Disassembly, Separation, and Purification

Finally, principle F aids end-of-life processing of products by designing for disassembly, cleaning, sorting, and part identification. Recycling, remanufacturing, reuse, repair, and, upgrading are all facilitated by incorporating features for disassembly, separation, and purification. These features are often found as structural solutions complementing principles A-E. For this reason, an example for principle F will be shown that also aids principle E.

Table 2-6: Principle F - Disassembly

F. Enable disassembly, separation, and purification by: [28]

49. Indicating on the product how it should be opened and make access points obvious[14, 17, 32, 34, 35]
50. Ensuring that joints and fasteners are easily accessible[34, 35, 38]
51. Maintaining stability and part placement during disassembly[15, 34]
52. Minimizing the number and variety of joining elements[17, 24, 31, 34, 35, 38, 41]
53. Ensuring that destructive disassembly techniques do not harm people or reusable components[15, 34, 38]
54. Ensuring reusable parts can be cleaned easily and without damage[15]
55. Ensuring that incompatible materials are easily separated[16-18, 34, 38]
56. Making component interfaces simple and reversibly separable[16-18, 32, 34, 38, 41]
57. Organizing in hierarchical modules by aesthetic, repair, and end-of-life protocol[14-18, 24, 32, 34-36, 38]
58. Implementing reusable/swappable platforms, modules, and components[15, 16, 18, 34, 36-38]
59. Condensing into a minimal # of parts[14, 16-19, 34, 37, 38]
60. Specifying compatible adhesives, labels, surface coatings, pigments, etc. which do not interfere with cleaning[14, 16-18, 24, 32, 34, 35, 38, 41]
61. Employing one disassembly direction without reorientation[17, 24, 32, 34]
62. Specifying all joints so that they are separable by hand or only a few, simple tools[17, 24, 32, 34, 38]
63. Minimizing the number and length of operations for detachment[24, 34]
64. Marking materials in moulds with types and reutilization protocol[14, 15, 18, 19, 24, 32, 34, 35, 37, 41]
65. Using a shallow or open structure for easy access to subassemblies [17]

Guideline F-57: Organizing in hierarchical modules by aesthetic, repair and end-of-life protocol; and

Guideline E-40: Improving aesthetics and functionality to ensure the aesthetic life is equal to the technical life.

Guidelines E-40 and F-57 help keep products functioning and current. Guideline E-40 points out that a physically durable component or product might be prematurely disposed because of aesthetics. Created with a "classic," aesthetically lasting design, a product can stand the test of time in usefulness and appeal to the consumer. Guideline F-57 suggests that designers organize the product to be upgradeable. Combining these guidelines suggests that modules might be upgraded for aesthetics as well as functionality.

Ford's Model U Concept Car from 2003 utilizes the combination of these guidelines. Figure 2-8 shows the interior of Ford's design using replaceable modules and common components for aesthetics and electronics.

Figure 2-8: Ford's Model U Concept Car has a Modular and Upgradeable Interior [45]

Modules that are removed during the use and upgrade of the vehicle are easily accessible and standardized. Upholstery, slots and electronic connections are arranged so the user can insert and remove electronics, seats and interior furnishings. It is a long-term, upgradeable investment, designed to please changing whims as well as needs [49]. At end-of-life, materials are organized into recyclable and biodegradable waste.

2.4 Chapter Two Summary

This chapter has reviewed and reconciled the existing green design guidelines into a single set of 6 principles and 65 guidelines. A variety of designers and researchers created these guidelines from decades of experiences to assist product designers in early stages of product development. Mind-mapping and four criteria helped create a uniform set of guidelines. Application of the three criteria of generality, designer orientation, and action-ability ensure usefulness of the guidelines for product designers across multiple domains and life-cycle stages. The fourth criterion–the positive imperative—focuses the guideline towards making positive and specific innovations, rather than correcting previous mistakes. Hierarchical organization of the set into principles and guidelines further distinguishes the goals of DfE (principles) from actionable suggestions for achieving those goals (guidelines). The resulting body of knowledge serves as an updateable, design tool for making preliminary design decisions.

Chapter 3: A Method for Identifying and Validating Guidelines

Guidelines have developed over time as new aspects of green design become relevant. Consequently, existing green design guidelines, presented in Chapter 2, are often concentrated more within historically important aspects of green design, such as end-of-life, rather than current and emerging topics, such as energy efficiency. Guidelines for end-of-life often stem from standardized practices, such as how materials are sorted and what tools are available on the disassembly floor. However, other stages, such as the use stage, are less standardized and guidelines are subject to additional performance metrics, beyond minimizing disassembly times and steps. Therefore, a systematic method is needed for developing and validating new guidelines relevant to emerging green design goals. This chapter presents such a method to explore environmental design opportunities targeted at the use stage of products.

Methods used to create design for environment principles prior to the systematic methodology in this chapter are largely undisclosed. It is inferred that most guidelines 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.

The method proposed in this chapter is intended for study of one representative set of products, so that the resulting guidelines can then be applied to other products within that product class without repeating the entire analysis process. The method combines typical aspects of product design, such as customer needs analysis, with reverse engineering and life cycle analysis. Chapters 4 and 5 demonstrate how this method can be used to develop and validate new guidelines for the next generation of green products.

3.1 REVIEW OF METHODS FOR CREATING GUIDELINES

One approach to creating green design guidelines and, more commonly, principles is deduction. They can be extracted from review of interdisciplinary literature and physical principles. Anastas *et al.*, for instance, present twelve principles for DfE [30, 50], but the results are too general to be easily applied to specific design problems, though it may put designers in a helpful frame of thought. Additionally, creating principles solely from literature 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.* [51, 52] approach the search for sustainable guidelines and principles by deducing them from the biosphere. 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 still being developed and requires an extensive knowledge base outside of many designers' expertise.

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 [53] and design for flexibility guidelines [54, 55]. Most of the procedures used to extract guidelines are either not presented or are created with limited scope and address a unique design problem or set of outcomes [14, 16, 38, 40, 41]. 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 [56] usually do not include customer needs analysis. Not incorporating such steps means not only missed opportunities and satisfying customer needs, such as product durability and usage. Possibly a direct result of this trend, most guidelines for durability address maintenance and upgradeability rather than resilience against failure. Therefore, the methodology proposed here combines well-known needs analysis and reverse engineering techniques [34, 57] with existing DfE guidelines and LCA metrics to create a holistic method creating guidelines.

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 [52]. For example, an old, vapor compression refrigerator consumes a fraction of the electrical energy of a new, thermoelectric refrigerator of similar volume. However, the thermoelectric device is much lighter, decreasing energy use in transportation. The thermoelectric also replaces hazardous refrigerants, decreasing non-energy, toxicological impacts. Because of the complexity of environmental effects, the proposed methodology incorporates LCA with reverse engineering and environmental requirements list. The method focuses solely on the usage stage of the life cycle because use of energy and water by products is relevant to modern green design. Additionally, 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.

The next section presents the methodology for developing green design guidelines. The method is centered on product utilization, including: assembly, disassembly, durability, and resources during use. In Chapter 4, the methodology is applied to a case study of energy use by thermo mechanical products. Application of the method produces a set of four new green design guidelines that can be applied to the design of future thermo mechanical products.

3.2 METHOD FOR DEVELOPING GREEN GUIDELINES

The methodology is derived from a combination of reverse engineering 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 [57]. Several steps are taken to customize a reverse engineering methodology for this application. First, the requirements list is extended to encompass environmental performance. Green requirements, as they are called in this paper, describe the environmentally friendly and environmentally harmful aspects of a product from the life-cycle perspective. Green requirements expose potential green redesign opportunities. Green requirements are identified by crosschecking observations from customer needs analysis, experimentation, and life-cycle analysis. Second, life cycle analysis supports two steps in the proposed method. It is implemented as part of the reverse engineering process to help identify environmental requirements with respect to existing products. Then, it is applied again at the end of the method to evaluate changes caused by redesign using the new guidelines.

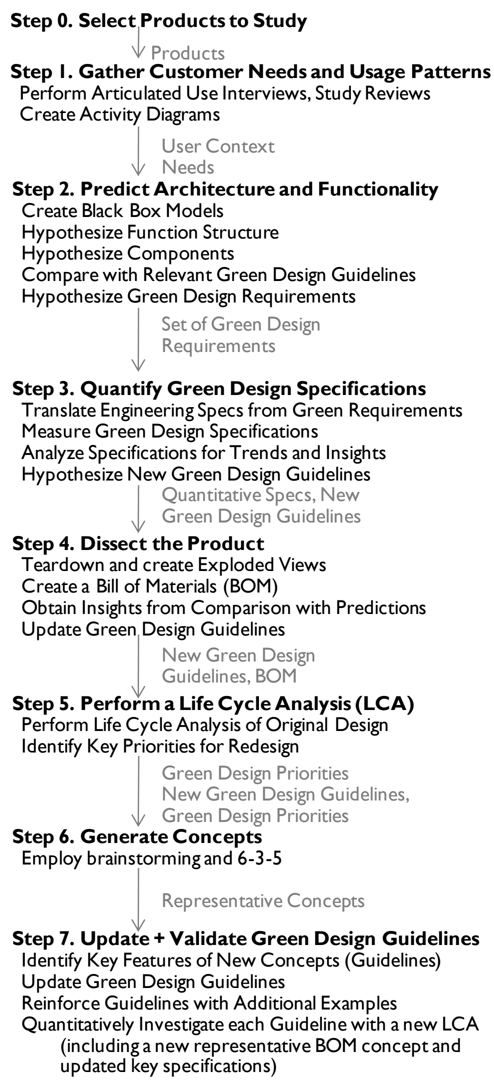


Figure 3-1: Method Flow Chart for Creating Guidelines

Figure 3-1 outlines the steps for identifying guidelines. Each step lists helpful tools or activities. The outcome of each step is shown connecting to the next step in the process.

Step zero defines the study by careful selection of products that embody future design problems. A class of products is chosen based upon its relevant functional characteristics. For example, a group wanting to improve outdoor water resource use might choose to form a study around sprinkler designs. Good sets of products provide unique human and architectural design aspects and exhibit both good and poor performance in the area of concern. Within the selected product class, three or more competing products are chosen. These products implement different design solutions to achieve the same function. It may be tempting to compare very different concepts, such as a sprinkler and a manual hose or an electric and stovetop kettle. However, the study should remain true to the functionality of the products; a sprinkler not only waters, but also automatically spreads water evenly. Range top kettles do not heat water, they merely hold water. The selected products must not only employ different architectures, but also fulfill the same functions.

In step one, the researcher begins creating green requirements by understanding the user requirements and the usage environment. Personally operating the products as well as surveying user comments allows one to interpret and record user needs and possible green requirements. A checklist for generating green requirements is shown in Figure 3-2. The list has been created from Pahl and Beitz's [15] requirements checklist using existing green design guidelines, presented in Chapter 2 and the Appendix, as well as the streamlined life-cycle analysis method created by Graedel and Allenby [58].

Main Heading	Examples
Consumables	*eliminate, biodegradable, efficiency extended use, renewable, properly disposed*
Controls	*most efficient settings, adjusts to use, shuts down when not in use*
Durability	*structural integrity, few moving parts, low rate of obselecence, aesthetically lasting, changeable*
Energy	*close to ideal, conserved, reclaimed sources, renewable sources, high efficiency*
Human Design	*encourages proper use, efficient use, good habits*
Hazards	*non-toxic, contained, reusable, proper disposal*
Materials	*toxicity, embodied energy, recycled, biodegradable, renewable, labeled, no excess*
Production	*simplicity, reliability, low waste, non-toxic chemicals, low energy*
Reusability	*modular, common components, recyclable, remanufacturable, easy to disassemble*
Transport	*lightweight, compact, small shipping volume,*
Maintenance	*easy to locate parts, easy to clean, upgradeable, modular, common components*

Figure 3-2: Green Requirements are Generated from the Green Requirements Checklist

As shown in the flow chart, articulated-use interviews are a suggested method for soliciting feedback and discovering latent customer needs [34]. Activity diagrams help map out the utilization process and interactions with other materials or concurrent activities [34]. The observations from this step highlight requirements in areas such as energy, human design, and durability in the checklist of Figure 3-2. The designer should complete step one with an initial set of green requirements, and an understanding of the product in the context most applicable to the study motivators (e.g. resource use, durability, or recyclability.)

In step two, the researcher revises and expands the green requirements 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 [15]. Black box diagrams help designers distinguish necessary flows from process choices (i.e. the input energy might not need to be electrical.) Building from 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 its output flows. Function structures are useful for disembodying current solutions and revealing alternative solutions from a subsystem or component standpoint [59]. At this point, the product has not yet been disassembled and the black box and functional models may be hypothesized.

Next in step two, it is helpful to sketch a schematic predicting the internal design. Creating one or more possible architectures helps designers brainstorm alternative designs. A predicted can be used to further identify good, bad or missed design opportunities as one would with a checklist [31]. 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 requirements.

In step three, the researcher quantifies the engineering specifications that relate to the products' green design needs. The goal is to correlate performance with measurable design characteristics—such as dimensions and performance parameters—that can be changed. For example, a green requirement 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. The house of quality (HOQ) is a well-known tool for correlating customer needs or performance criteria, with measurable engineering specifications [34, 60]. After the engineering specifications affecting the green performance of the products are identified, they can be measured with respect a 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. These insights will take the form of new green requirements as well as possible guidelines for satisfying green requirements already recorded in the previous steps.

At this point in the study, green requirements will have been revealed from three perspectives: usage, observation, predicted functionality, and engineering specifications. An initial set of potential new guidelines will form as well. These guidelines should be recorded in a form that is as actionable, general, designer oriented, and reflective of best practice as possible [61].

In step four, researches create a BOM and link actual products' architectures to their performance. Disassembly and discovery of the actual product architectures may reveal different functions and design solutions than previously envisioned. Creation of a Bill of Materials (BOM) from the disassembly is necessary to perform life cycle analyses as well as to create the basic BOMs for redesigning in step seven. At the conclusion of product dissection, the list of possible new guidelines can be expanded and clarified.

In step five, researchers learn the impacts of current design decisions through LCA. Life cycle analysis helps prioritize redesign goals and 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. LCA results can then help inform the redesign tasks.

In step six, new product concepts are proposed to meet the green requirements list. 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 [15, 34]. 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 new concepts 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 meet the green requirements with each embodiment. These guidelines are then reinforced by finding analogies in other product embodiments that exist outside of the domain or set of products being researched. This exploration will help mold the final guidelines into a more general, but actionable form.

Once the guidelines are established, a new design concept and BOM guideline is created for each guideline, to represent the product *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 are 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. These redesigned BOMs are used for LCA to investigate whether applying the guidelines improve environmental impact. It may be necessary to carry out further experiments, calculations or modeling to update the life cycle inventory of the concept. The results of the LCA-based validation are only applicable to the class of products investigated in the study. Though determination of the guidelines' effects in other product domains requires further research, hypotheses can be made 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 intended for the early stages of design, when formative decisions are made and LCA is not feasible.

In the following chapter, 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.

3.3 CHAPTER THREE SUMMARY

This chapter outlined a new method for analyzing benchmark products to create green design guidelines for future concept generation. The method relies upon the combined strengths reverse engineering, life cycle analysis, and green design. The methodology can be used, as described in this chapter, to create guidelines in multiple areas of product utilization, such as resource use, durability, and even ease of disassembly.

The following section presents a case study that successfully applies the proposed method to electric kettles. Details for each step in the case study show how the green design guidelines developed through use of the methodology. The method leads to the discovery of four new guidelines that reduce the kettles' resource consumption during use.

Chapter 4: Case Study of an Electric Kettle

In this chapter, a case study of electric kettles shows how the methodology developed in Chapter 3 is useful for generating guidelines. Applying the method to the benchmark products yielded four new guidelines that reduced resource consumption during the consumer-use phase of the life cycle. The guidelines were also validated and explored through LCA. Examples of additional products that implement the guidelines provided evidence that they are useful for a diverse set of design problems.

4.1 Step Zero: Selection of the Products

Electric kettles were chosen for the study because they are power intensive during the use phase. Energy use was believed, and later verified, to constitute a majority of the environmental impact of electric kettles. They were chosen to represent similar, low-obsolescence, high-power kitchen devices with few parts that might be redesigned using guidelines created by the case study.

Different heating designs dictated the selection of three kettles. Table 4-1 lists the three products and summarizes their differences in terms of heating elements, insulation, power ratings, and other energy aspects. A Proctor Silex kettle was chosen because it was the most inexpensive, had the lowest power rating, and was the smallest kettle available. It also had a unique, coil heat exchanger. A Capresso H2O Plus was chosen because it was made out of glass rather than 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. Each kettle offered different advantages, from the thicker walls of the

Capresso kettle, to the high power rating of the Braun AquaExpress. The advantages of different power ratings, heating elements, or covers were assumed for step zero.

Table 4-1: Products were Chosen by their Functional Designs

			 Images from Amazon.com
Kettles	Braun AquaExpress	Capresso H2O Plus	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

4.2 Step One: Gather Customer Needs and Usage Patterns

The kettles were then 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 impatient users would manually stop heating, as noted in informal customer interviews. Earlier shut off presented an opportunity to reduce energy. Second, customer reviews indicated that forgetful users wanted a signal when their water finished boiled. Energy would be lost if water were forgotten and left to cool; 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 needs, though the amount of heat lost to steam varied.

4.3 Step Two: Predict Architecture and Functionality

A black box diagram, with the primary task of boiling water, revealed the energy, material, and signals entering and leaving the kettle.

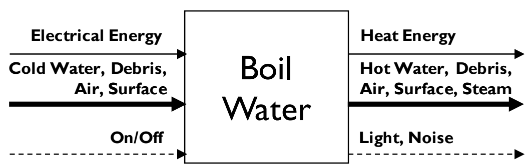


Figure 4-1: The Black Box Model of an Electric Kettle shows Generalized Process Choices

The kettles' black box representation, Figure 4-1, 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 requirement 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.

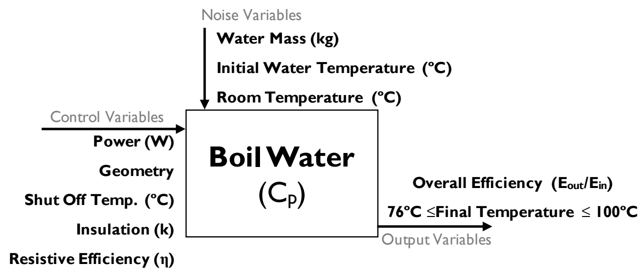


Figure 4-2: P-Diagram

Based on insights obtained from the black box, a P-diagram, Figure 4-2, 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 p-diagram shows that the design cannot directly change water intake. A passive influence of the design might be 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 also processing functions that can contribute to the efficiency of the kettles. These functions are shaded in the hypothesized function structure in Figure 4-3. The expanded functions addressed the variability in final temperature and water mass and met a new green requirement 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 requirements 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 requirements for redesign and initiating a list of possible new green design guidelines, the kettles were compared with existing green design guidelines to make the list of needs as extensive as possible. The existing guidelines for resource efficiency are shown in Table 2-3, in Chapter 2**.**

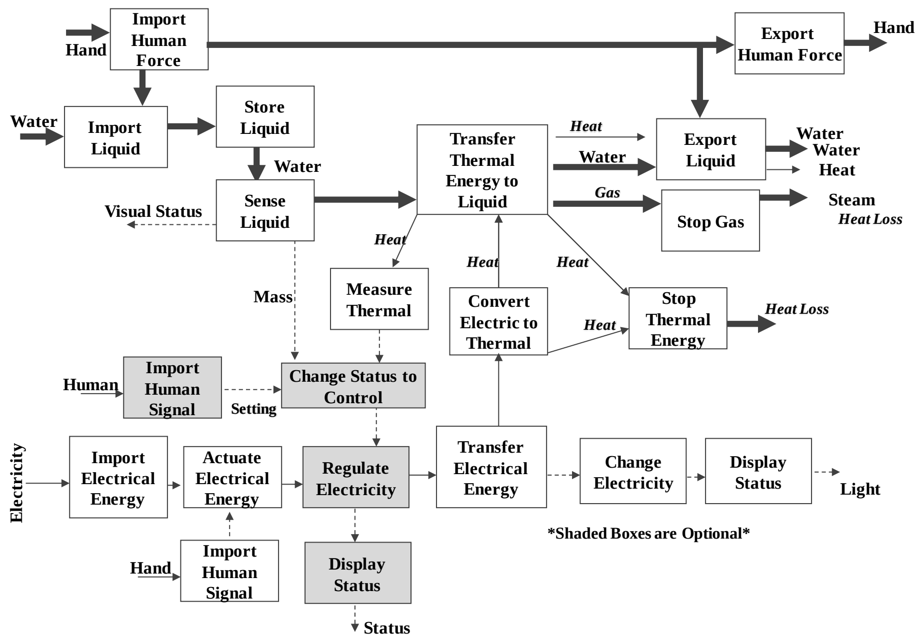


Figure 4-3: The Expanded Function Structure Shows all of the Relevant Function

The kettles and their operations were compared to the green requirement generators introduced in Chapter 3, Figure 3-2, and analyzed using the guidelines under Principle D in Chapter 2 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 met by the products or were not applicable 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. The checklist in Figure 3-2 introduced factors of human design that contribute to energy efficiency. The checklist combined with the steps one and two of the methodology yielded the following green requirements with accompanying opportunities for new 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 cleaner, more 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 rising out.

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. It was noted from reviews and experience that the kettle might be forgotten or hot water left cooling long enough that the user would be compelled to reheat the contents and "waste" energy reheating the water.

4. **Optimize Individual Runs/Processes to Outcomes**

Possible New Guideline:

Incorporating dynamic or static tuning capabilities for certain processes

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.

4.4 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 requirements, p-diagram, and potential guidelines revealed in previous steps.

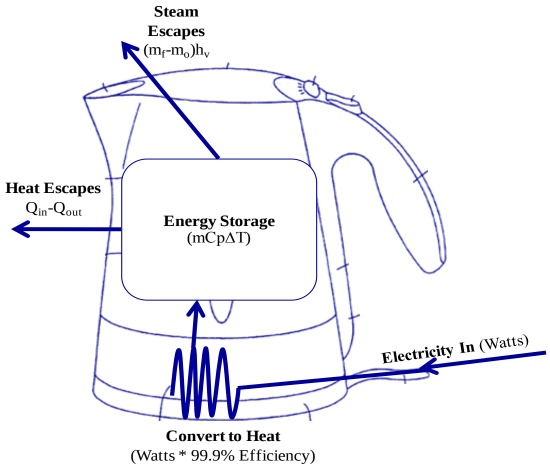


Figure 4-4: Energy Flows Into and Out of the Kettle were Estimated

The basic operation of each kettle is shown in Figure 4-4; it 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 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 4-2, all three kettles were observed to heat past visual boiling, resulting in varying overall efficiencies.

Table 4-2: The Energy Study Shows the Energy Saved by Heating to 95ºC

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%

Visual boiling seemed to 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 4-2. The Capresso exhibited the highest efficiency because it stopped heating at a much lower temperature than its competitors did. In contrast, the Braun exhibited the lowest initial efficiency because it shut off after extensive over boiling.

From this experimental study, it was evident 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*.

At the end of step three, the operations of the kettles had been thoroughly explored to reveal four green requirements and five 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.

4.5 Step four: Dissect the Product

Disassembly of the kettles revealed that the internal components across all three designs were similar. The exploded view of the Capresso kettle is shown next to the

Proctor Silex kettle in Figure 4-5. The architecture and functionality of the kettles had been predicted fairly closely and no further insights were gained by discovering the actual components. There were no components in any of the kettles to meet the green requirements or follow the new guidelines suggested in earlier steps.

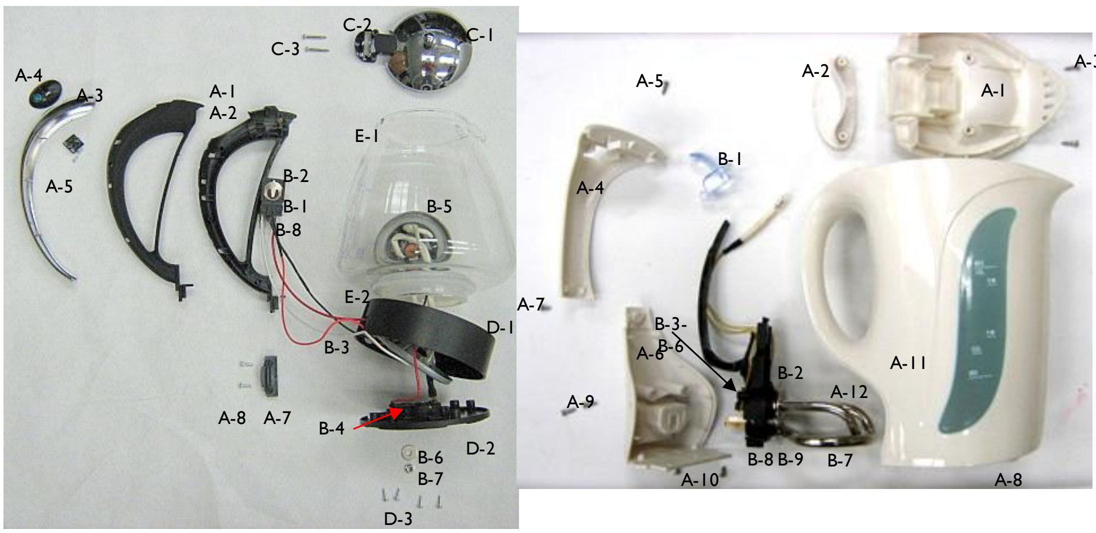


Figure 4-5: Exploded View of the Capresso and Braun Kettles Display all Major Components

Teardown of the kettles resulted in a bill of materials (BOM) for each kettle, shown in the Appendix. 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.

4.6 STEP FIVE: PERFORM A LIFE CYCLE ANALYSIS

Before beginning brainstorming of new concepts, an LCA of the Proctor Silex kettle was performed to investigate the most environmentally impactful aspects of the kettle's design. As part of the LCA, the functional unit of the electric kettle had to be specified. 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 [62, 63]. Appendix A shows images of the flows mapped in GaBi software. 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) [63, 64].

Table 4-3: The Useful Life of the Kettle Dominated its EI Score

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

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, shown in Table 4-3. 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.

From these results, it was concluded 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.

4.7 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, Figure

4-3, the black box diagram, Figure 4-1, the p-diagram, Figure 4-2, and the list of pre-existing guidelines.

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 [34] 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 requirements. 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.

4.8 Step seven: Analyzing 6-3-5 and Updating 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.

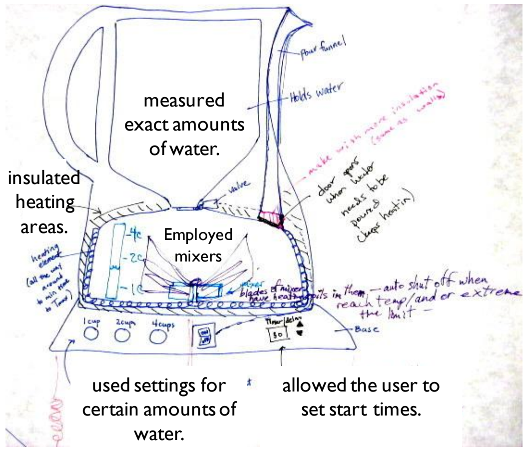


Figure 4-6: One 6-3-5 Concept Incorporated Many Solutions

Figure 4-6 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.

4.9 Step seven: Validate Green Design Guidelines

The final set of new guidelines was supported by identification and analysis of existing examples. These examples are discussed in this section and followed by results of LCAs of the kettle redesigns.

4.9.1 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.

Figure 4-7: Tankless Water Heaters Use 75% of the Energy of a 40 Gallon Tank System [65]

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. There are several advantages and disadvantages when considering the life cycle impact of a tankless water heater in comparison to a tank heater. Firstly, the tankless heater does not require a tank. A 60gal Superstor tank is approximately 98lbs of steel, copper and insulation [65]. The DOE estimates that tankless water heater systems use 28% less energy than a typical 40-gallon tank heated system [66]. Additionally, tankless water heaters have useful life expectancies of 20-30 years, while tank water heaters reportedly last 10-15 years [67]. Disadvantages are that tankless heaters may require extra circuits or gas lines to help power the system and cold water may be wasted while users wait for hot water to arrive at their faucet.

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. Water consumption is halved if a user takes the same length of shower using a 2.5GPM shower head versus a 5GPM shower head. This amount of water is saved every shower, about three to ten times per week for most people, and only requires enough extra stainless steel for a flow limiting valve. Additionally, in some hostel or public showers, the showers incorporate automatic shut offs that require the user to restart the water at selected intervals to encourage bathers to spend less time showering or only use the shower when rinsing.

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 to combinations of products, such as a washer and a dryer, that are linked by common activities.

4.9.2 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 visible 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. A rough estimate of the changes in lifecycle impact of a Caroma Dual Low Flush Toilet in comparison to a regular low flush toilet shows that the Caroma saves about 12L of water each day. This calculation assumes a 3L Liquid Flush, and 6L Solid Flush with a daily use of one Solid and four Liquid flushes [68]. To accomplish these water savings, the whole toilet requires only a small amount of stainless steel and plastic to create the extra stem and button, shown in Figure 4-8.

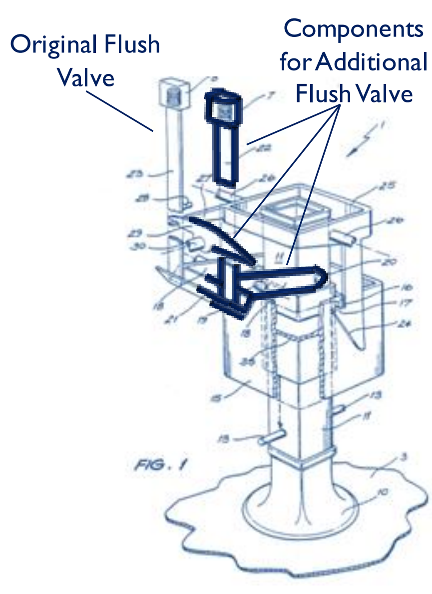


Figure 4-8: Additional Flush Stem Prematurely Closes The Valve [69]

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 [70]. It seems that automatic and even manual tuning can provide a simple means for significant reduction in resource use.

4.9.3 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 with respect to customer needs and the product's function, and should be distinguished from solutions that monitor energy or water input irrespective of the customer's desired outcomes, as described by Guideline D-10 in Table 2-4. 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 the use of feedback mechanisms to save resources, particularly heat energy. Many new ovens provide temperature readings and alarms to notify users that the oven is preheated and not left on too long. 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. While having this ability is useful to maintain the temperature in an oven, its energy efficiency and environmental impact is questionable. A glass pane and a lighting fixture, as in **Error! eference source not found.**, must be installed to allow a user to check the status of their food while it is in the oven.

Figure 4-9: Glass Windows and Light Bulbs Help Users Monitor Oven Operation

A disadvantage of glass panes is insulation. A double, glass paned oven door would have approximately 50% more thermal resistance than a steel door with insulation, assuming a 5cm thick door with 3cm of insulation or air. This guideline thus reduces heat loss during operation and prevents heat lost when checking on food.

4.9.4 New Guideline 4: Creating separate modules for tasks w/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. Hybrid electric vehicles have a net reduction in green house gas emissions over their lifecycle, but the environmental safety of their batteries is dependent upon proper handling and recycling [71]. 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. The eco-kettle isn't much larger than a typical electric kettle and requires additional components for the separate storage tank and release valves.

4.9.5 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 4-4 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 4-4, 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.

Table 4-4: Each of the Guidelines inspired a new Kettle Design and incurred a different Environmental Impact score

#	Guideline	Redesign Concept	Replaced Components	New Components	Energy Saved (1 kg)		Change in E.I. Score	
1	Minimizing the quantity of resource use by optimizing between its rate and time.	Earlier Shut-Off (95°C)	Bi-Metallic Switch	New Bi-Metallic Switch	52 kJ	12%	-624 mp	5% Reduction
2	Incorporating automatic or manual tuning capabilities.	User Sets the Shut-Off Temperature (76°C - 100°C)	Bi-Metallic Switch	Thermocouple, Circuit Board, Dial/Potentiometer, Switch	164 kJ	38%	-1700 to +249 mp	14% Reduction to 2% Increase
3	Using feedback mechanisms to inform the user of current status of the process.	Displays Current Water Temperature	N/A	Thermocouple, Circuit Board, Display Screen	37 kJ	36%	-245 to +197 mp	2% Reduction to 2% Increase
4	Creating separate modules for tasks w/conflicting requirements/solutions.	Measuring Cup for Water	Remove Viewing Area	Measuring Cup	2kJ	0.50%	-10 mp	0.08% Reduction

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 too much. 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, the guidelines led to energy savings, but not necessarily a reduction in life cycle impact. If the new features were not utilized, energy was not saved during use and the additional components increased the life cycle impact. Most guidelines are associated with environmental tradeoffs; Energy savings, for example, can be offset by high-embodied energy or hazardous components. The other product examples for each guideline show that this tradeoff does not always occur; Application of the guidelines to other design scenarios leads to unique component changes, additions, or reductions.

4.9 Chapter Four Summary

When applied to a case study of electric kettles, the methodology successfully revealed four previously unpublished guidelines for resource efficiency during product use. These guidelines were: (1) Minimizing the quantity of resource use by optimizing between its rate and duration. (2) Incorporating automatic or manual tuning capabilities. (3) Using feedback mechanisms to inform the user of the current status of the process. (4) Creating separate modules for tasks with conflicting requirements or solutions. For each guideline one or more existing examples of products were found that save energy or water by employing that guideline.

Comparisons of the Proctor Silex Kettle's LCA and hypothetical LCAs for each new guideline showed the total life cycle effects of the guidelines. Two observations were made from the results. Due to human behavior effects, guidelines one and two improved performance more reliably when applied in tandem. Besides the possible improvements in environmental impact, it was shown that additional components can outweigh possible energy savings, and such tradeoffs must be carefully assessed.

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.

Chapter 5: Evaluating the Usefulness of New Guidelines

While the preceding chapters have addressed current green design guidelines and the development of new green design guidelines, they have not addressed the usefulness of green design guidelines for concept generation. The method presented in Chapter 3 is intended to shorten design time by helping develop guidelines that can be used in future design efforts. The case study in Chapter 4 shows how the method helped develop four new green design guidelines, but does not indicate whether or not the guidelines are useful in future applications. Existence of the guidelines in other product examples suggested a wide range of applicability. However, the utility of the guidelines requires that they yield greener concepts when used as a concept generation tool.

In this chapter, a concept generation experiment is conducted to investigate the hypothesis that guidelines are useful for the design of new products. The experiment's problem statement asked participants to design a toaster and included the four new design guidelines as a concept generation tool. A second group of participants designed the toaster without guidelines. The results showed that designers who had guidelines created more green concepts than designers who did not have guidelines. The results are consistent with the hypothesis, but require further testing to be conclusive.

5.1 EXPERIMENT OVERVIEW

The objective of the experiment was to determine if the new guidelines increase the number of green concepts identified during concept generation. A concept generation experiment challenged designers to design a new, energy-efficient toaster using the four new green design guidelines. Designers were asked to brainstorm and sketch concepts using only the information given. Resulting concepts were analyzed to determine if they were viable and offered environmental benefits relative to a standard toaster. Results were compared with those from a second group of participants who generated concepts for the same problem statement, but without guidelines. A higher number of viable, green concepts for the guidelines group would support the hypothesis that guidelines are useful for generating green concepts.

5.1.1 Problem Statement and Procedure

Participants were given three days to generate concepts for the following problem statement:

> In order to meet the need for energy efficiency and reduction in our current society, we must innovate and think outside of the box to re-approach even the simplest of tasks. Making toast is an energy intensive process that uses a fairly simple heating device, a toaster. Because it incorporates small, simplistic components and uses a high power input, a large part of a toaster's environmental impact is its energy during use. *Your challenge is to create the next generation toaster that uses as little energy as possible to meet the basic customer needs for toasting.*

Both groups were supplied with the following set of customer needs for toasters, taken from Otto and Wood [34]:

- Toast Multiple Slices
- Inexpensive
- Compact
- Uniformly Toasted Area

- Toasts Bagels and Bread
- Used in a typical residence

Each participant was instructed to spend a total of two hours on the problem, using half an hour each for brainstorming and mind-mapping [34] ideas and an hour for sketching concepts.

Two concept generation groups comprised the experiment. Each group consisted of five participants, with little, personal knowledge of green design. Each group received identical problem statements and information, with the exception of the green design guidelines. The control group did not receive concept generators while the guidelines group was exposed to the four new green design guidelines from Chapter 4. Participants in each group all held bachelor degrees and are current or recently graduated masters students in mechanical engineering. Groups had equal numbers of participants specializing in energy and design.

After the sketches, lists, and mindmaps had been collected from each of the groups, they were analyzed for unique features and compared. The method of analysis of the concepts is described in Section 5.2. Features were separated, evaluated for viability and practicality, and scored against existing green design guidelines in comparison to a simple, benchmark toaster. Statistical analysis was then performed to discover the average number of features generated by each participant in a group as well as the standard deviation and confidence interval for the difference in means between the guidelines group and control group.

5.2 EXAMINING CONCEPTS FOR GREEN FEATURES

Any concept generation session is a chance to uncover possible features of a product. Each feature is a separate solution to a different function of a product or concept. For the purposes of this analysis, features are disambiguated by their solution principle, explained later in this section. During the design process, members of a design team contribute ideas for features. A design team creates a final concept by combining and augmenting these solution principles as working principles and embodiments [15]. If the guidelines are helpful to create a larger number of green design concepts, then the expectation is that the guidelines group of the study should produce more green features.

5.2.1 Delineating Features

Concepts were first delineated into features using an expanded function structure for a benchmark toaster, shown in Figure 5-1. Functions related to the flow of energy are in white and comprise the functions of interest for this study. Each feature in a concept was a solution to one of these functions. These features were recorded in a morph matrix of the relevant functions and each participant's concepts, with a short description of each feature in the appropriate row and column (see Appendix I.) Practice between two researchers found that better agreement in naming features was reached if they were described using short verb phrases, such as sits over gas burner, rather than less similar nouns or component names, such as gas burner or stove top.

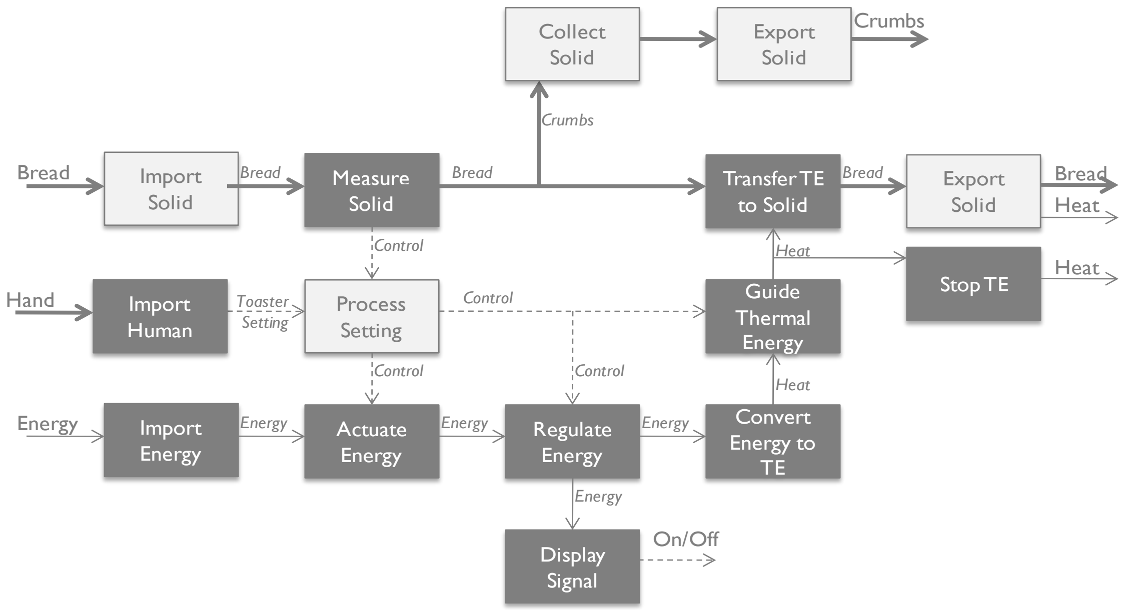


Figure 5-1: An Expanded Function Structure of a Toaster was used to Identify Features

Features were distinguished primarily by solution principles, but were also distinguished by energy domain. The idea of separating features using solution principles and working principles has been used successfully in concept generation research [72, 73]. Pahl and Beitz describe a solution principle as being independent of the working principle to a problem. For example, solution principles for converting input energy to thermal energy were rubbing frictional materials or burning gas for heating toast. Working principles often combine solution principles with geometry and material characteristics, but were not considered of sufficient uniqueness that the number of working principles would significantly change the outcomes of concept generation [15]. Two examples for working principles to fulfill the solution principle of friction are using rotational motion to rub the frictional materials and using translational motion. Such differences in working principles have little effect on the environmental performance of a product and were considered identical features. In further analysis, features were evaluated based upon the most favorable working principle.

One exception to the rule of separating features by solution principles occurred when distinguishing the working principles of infrared heating coils and infrared heat lamps as different features. This separation was made because many designers specified resistive coils but not the form of energy and it could not be determined if these designs used the solution principles of convection or radiation. Resistive heating was a popular choice for converting energy, but took multiple forms. Resistive elements were used for creating convective and conductive heat as well as radiative heat from infrared light. Because the three forms of thermal energy are very different, the three working principles, resistive-convective coils, resistive-conductive plates, and resistive-infrared coils were considered analogous to different solution principles and were therefore three different features. The final separations were resistive plates, resistive coils, and heat lamps to represent solution principles of conduction, convection and radiation, and radiation respectively. As noted earlier, embodiment itself was outside of the scope of the study and assumed to be as environmentally friendly as possible when evaluating possible life-cycle impact.

5.2.2 Evaluating Features

Features were counted towards each group's results if they were determined to be viable, practical and green. Many features created in concept generation are not technically viable or practical for new product lines. The goal of the guidelines is to create feasibly greener and more energy efficient features and therefore only those features satisfying the goals of the guidelines were counted towards a group's ideation performance. Though it was not possible to experiment and model all of the proposed features, only energy features that were viable, practical and had the potential to improve the net environmental footprint of the new toaster in comparison to a simple, benchmark toaster were counted. Figure 5-2 shows the decision flowchart for evaluating features.

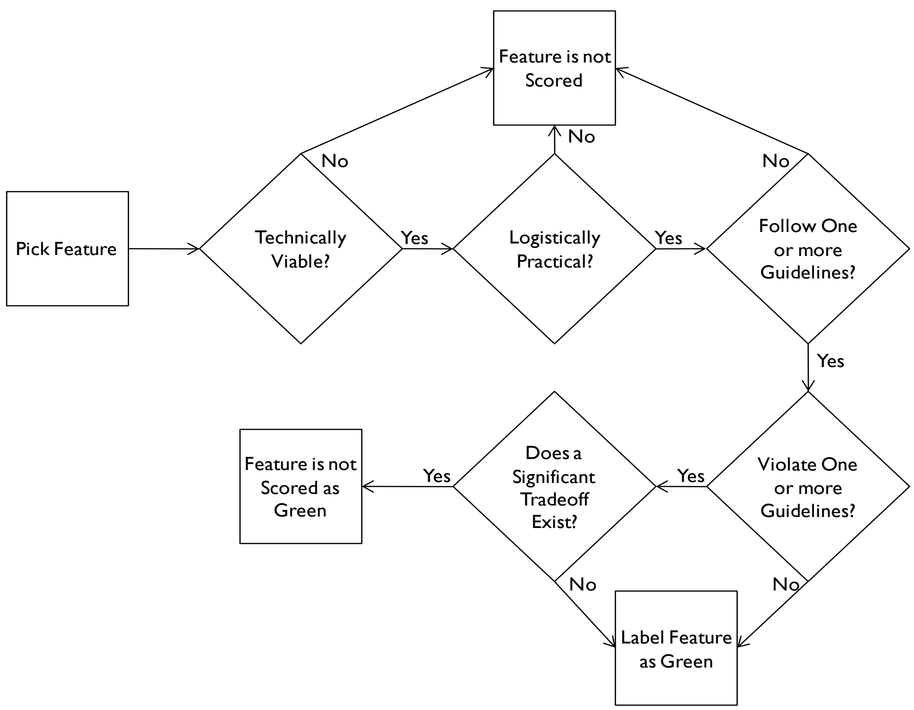


Figure 5-2: Features were Evaluated According to the Flowchart

This section will give examples of analysis for each decision node in the flowchart. Explanations of the decisions for each feature are in Appendix I.

A feature was considered viable if there were no insurmountable technical barriers in the immediate future. Features that failed viability were those that could not harness the required energy because of either their implementation or the current state of technology. Popular examples of unviable concepts are jetpacks and nuclear fusion. A human simply cannot carry the necessary fuel for a jetpack to work. Nuclear fusion currently only works experimentally for a few seconds.

Figure 5-3 depics a concept from the control group that exhibited a non-viable feature described as "place weight" for importing energy.

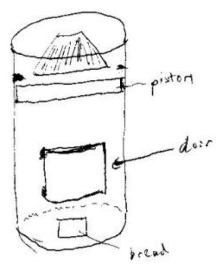


Figure 5-3: The "Place Weight" Feature Fulfilling the "Import Energy" Function

To determine the viability of this feature, the footprint of a typical kitchen and the physical abilities of a typical consumer were used as constraints. If the weight were manageable by a consumer, 10lbs or approximately 50N, the weight would need to compress a distance of at least 1200 meters to impart 60kJ of work. Traveling one half meter, the weight would need to be 120kN or approximately 24,000 lbs. These values are not within reasonable ranges for kitchen area or consumer strength. Using a mass as a driving force to compress air and create heat is therefore not viable.

A viable feature was considered practical if it did not have any insurmountable logistical, integration or economic barriers. Some technologies will work but come at excessive cost, cannot work in a typical consumer's home, or do not make logistical sense when considering a toaster's primary residential use. Practical needs can be deduced from considering the customer needs from the problem statement as well as assuming that the toaster is used in a typical residence before noon and only in conjunction with other morning, kitchen activities.

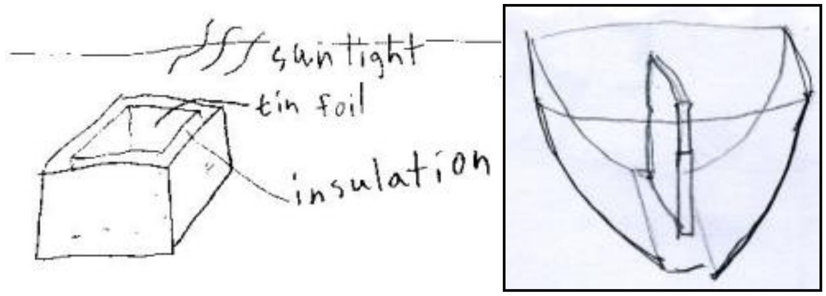


Figure 5-4: Both Groups Proposed the Viable but Impractical Solar Oven Concept

Figure 5-4 shows two concept sketches for a solar heated toaster. The concepts were deemed viable by considering locations in the United States with very good and very poor solar exposure. The calculations assumed 0.14 kW/m^2 of solar insolation in New England and 0.32 kW/m^2 in Texas. If the toaster held two slices of bread and had a perimeter the width of one slice of bread, the toaster would be able to toast bread after 25 minutes of steady insolation in Texas and 60 minutes in the northeastern Unites States. However, this range of 25-60 minutes was deemed impractical as current toasters take one to two minutes and customers would likely not want to spend more than 25 minutes toasting bread for breakfast. Additionally, considering a normal routine, toast is usually made when solar heat is least available, at, before, or soon after sunrise.

Features that were viable and practical were then compared with the existing list of guidelines presented in Chapter 2 and the four new guidelines from Chapter 4 to determine whether or not they are green. It was noted which guidelines the features followed and which guidelines they violated. If a feature did not follow any guidelines, it was not considered green because it offered no improvement over the current benchmark toaster. If it did follow guidelines and did not violate any guidelines, then it was determined that the feature can be considered green and offer an improvement over the current benchmark design. If the feature both followed and violated guidelines, a best guess determined whether or not there was a significant tradeoff making the overall environmental footprint higher than the benchmark toaster. For example, the feature of a solar panel and battery for powering the toaster, shown in Figure 5-5, did not have obvious significant tradeoffs.

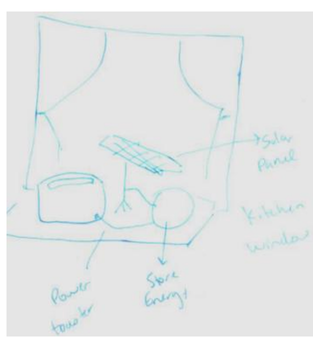


Figure 5-5: Solar Panel with Battery Feature Did Not Have a Significant Tradeoff

This feature was considered viable because a solar panel operating at 12% efficiency with full solar exposure and no battery losses could obtain the necessary energy over a day in the northeastern United States with only 0.02 m^2, approximately the area of a piece of bread. The feature was also considered practical as a solar panel and high power battery would bring the cost of the toaster within the current cost range of $10-$130, assuming $20 for the solar panel, $50 for the battery and $10 for the toaster at large scale manufacturing. This solution could be combined with an outlet cord as back up if the kitchen lacks solar exposure or is not able to obtain the required energy.

Table 5-1 lists the guidelines followed and violated by this concept.

Table 5-1: The Solar Panel and Battery Feature Violated More Guidelines

Followed Guidelines	Violated Guidelines
1. Specifying the cleanest source of energy	1. Minimizing the number of components 2. Specifying non-hazardous and otherwise environmentally "clean" substances, especially in regards to user health

The environmental impact of the toaster could be increased by the battery and solar panel, if not enough grid energy is replaced. Payback on the energy to make a solar panel is estimated at four years [74]. The toaster would therefore need to operate for longer than four years to payback the costs of a solar panel *and* battery. Additionally, Stevels et al. concluded from LCAs of differently powered radios that the impact of batteries depends upon their end of life strategy [75]. Assuming that the toaster is mostly solar powered over a ten-year life span and the batteries are fully recycled, the environmental impact of a solar toaster could be lower than a benchmark plug-in toaster. The best-case scenario suggests that the solar panel and battery could reduce net life cycle impact without a significant tradeoff.

5.2 EXPERIMENTAL RESULTS

Final analysis of the concept generation results suggests that the guidelines directly and indirectly helped participants create green concepts. Following the analysis described in the previous section, the guidelines group produced 20 viable, green features while the control group produced only 10. Together, the participants created 24 unique features. The guidelines group shared more than half of the features discovered by the control group, suggesting that the guidelines encouraged more exploration of the design space. As expected the control group rarely found solutions that utilized the guidelines, while the guidelines group used the guidelines more often, contributing to a third of participants' unique features.

Using separate controls for toasting slots is an example of a unique feature offered by the guidelines group that uses two of the new design guidelines. As shown in Figure 5-6, separate slot controls reduce energy use by 1) Incorporating automatic or manual tuning capabilities and 2) Creating separate modules for tasks with conflicting requirements or solutions.

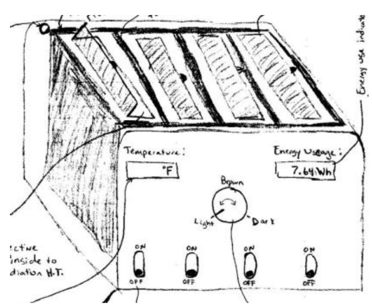


Figure 5-6: Sketch of Separate Slot Controls

Most toasters have two or more toasting slots, assuming users will always toast two slices at once. Most toasters heat empty slots and waste electricity. The new concept allows users to toast one to four pieces of toast individually. A disadvantage is the manufacturing costs of each separate control. Another concept, shown in Figure 5-7, offered by the guidelines group, independently improved upon this design with a similar feature that still allowed individual slot control, but combined the controls into one component.

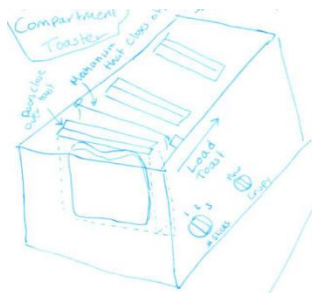


Figure 5-7: Sketch of Combined Slot Controls

In contrast to the guidelines group, the control group tended to focus on changing source and conversion of energy, rather than controlling the processing of heating. Complete concept sketches are shown in Appendix H. Control group participants used design time pursuing concepts that use waste heat and combustion rather than considering more feasible concepts. These features appeared twice as often in the control group as in the guidelines group and contributed to the low number of viable features.

Despite the superior performance of the guidelines group, the results are still inconclusive. Table 5-2 shows the results for the guidelines group and the control group;

Group results account for each feature once per group while statistical per person analysis counts each feature once per person who implements it.

Table 5-2: Results Suggest that Guidelines are Helpful but Require Further Study

	Features that Meet Guidelines	Features without Significant Tradeoffs	Unique Features Without Significant Tradeoffs	Different Features per Person (Average)	High per Person	Median per Person	Low per Person	Standard Deviation	95% Confidence Interval (Increase in Mean)
Guidelines Group	33	20	14	5.6	9.0	8.0	0.0	2.1	1.4 +/- 3.9
Control Group	19	10	4	4.2	6.0	3.0	3.0	0.8	

On average, participants in the guidelines group generated more features than participants in the control group. The guidelines group yielded a much higher median number of features per participant. The hypothesis that applying green design guidelines leads to a greater number of green concepts is corroborated by the guidelines group's performance and therefore, the case study results are promising. However, the variability in performance of the participants and the small sample size contributed to the large standard deviation and confidence interval shown in Table 5-2. At 95% confidence, the data suggest that a group with guidelines can produce anywhere between six more and three fewer features per person.

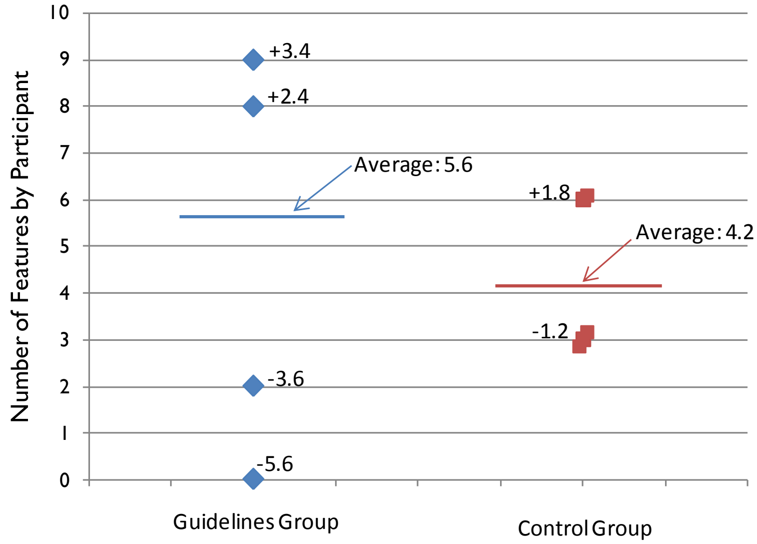


Figure 5-8: Variability Among Members of the Guidelines Group Suggests that using Guidelines is not Intuitive

Individual performance, plotted in Figure 5-8, varied more for the guidelines group than the control group. Participants in the guidelines group performed either very well or very poorly. The reason for this disparity is unclear. Certain participants may have lacked the necessary skill or time. The guidelines may not have been as intuitive to some of the participants as others.

5.2.1 Possible Study Improvements

The initial case study provides one example of how the guidelines might help generate a larger selection of greener concepts. The success of these design groups suggests that further study with statistically conclusive applications of green design guidelines would be worth pursuing. Lessons from this study suggest that improving presentation of the guidelines and a much larger study with more design-oriented participants will provide more conclusive results supporting the use of guidelines.

Informal surveys of the participants in the guidelines group showed that the participants used the guidelines during brainstorming, but did not concentrate on using them during sketching. Instead most participants said they used the guidelines subconsciously or when they looked back to get more ideas during sketching. Because the guidelines group used guidelines more than three times as often as the control group, it is likely that the guidelines had a subconscious influence as stated in surveys. Some participants did not use the guidelines and created very few or no viable features. Thus, more study is needed to improve presentation of the guidelines so that they are more accessible as a design tool.

It is not clear that participants would have used the guidelines more effectively if they had been given examples, as suggested in surveys by Lofthouse [76]. Examples can create design fixation upon previous solutions and limit the design space. Additionally, unique products call for unique applications of guidelines. For example, a user monitors the status of boiling water by checking the temperature of the water, but a user of a toaster usually gauges the brownness of their bread and gains nothing from temperature readings. One of the guideline group’s concepts featured a temperature display, but the feature was not considered green because it was irrelevant to the performance of a toaster. Three other features from the guidelines group provided similar examples. It is possible that the use of guidelines should be explained using guidelines for areas other than green design.

Though the general performance was favorable, the size of the sample was too small to overcome noise from variability of the participants. Linsey lists participants' individual cognitive abilities, expertise, culture, motivation and receptiveness to tools as common noise factors in design method studies [77]. Participants of the study may have been under mental stress at the time and not read the instructions very well or explored the design space very well because they were not properly motivated. All participants were volunteers and received no compensation, other than recognition, for their contribution. Additionally, both groups had a spread of participants. Some participants had expertise in high-level energy analysis while others focused on less broad areas of energy. Some participants were very familiar with design and brainstorming, while others were only slightly experienced. By looking at the spread in results, it is possible that some of the participants in the guidelines group are less familiar with open-ended design problems while members of the control group may have been more comfortable. A larger sample of more experienced designers can more realistically determine whether or not the results from this preliminary study are indicative of designers in general and green design guidelines are indeed helpful for concept generation.

5.3 Chapter Five Summary

This case study showed that guidelines can increase the number of green concepts created during concept generation. The guidelines helped study participants double the number viable, green toaster concepts. Specifically, the guidelines may have helped break fixation on energy conversion within the toaster. The scope of redesigns by the guidelines group encompassed process control in addition to energy conversion. Though the results are encouraging, the current sample size does not provide any statistical significance. It is probable that a larger sample size of design engineers will support the guidelines more conclusively. Additionally, future studies should include brief instruction of how guidelines can be used.

Chapter 6: Contributions and Future Work

Before this work, green design guidelines were primarily presented and created as solutions to a single life cycle stage rather than as part of a system of solutions for all stages. This work has assessed the current status of green design guidelines for environmentally conscious design and addressed these shortcomings of traditional green design guideline development and preservation. This chapter revisits some of the major contributions and conclusions of the previous chapters and suggests avenues for further research projects.

6.1 Research Contributions

The first contribution of this work is a unified set of the pre-existing green design guidelines found in literature. The resulting list of guidelines reconciles differences in level of detail, audience, and scope of existing green design guidelines and principles. Review of design for environment literature helped form four criteria that can be applied to phrasing guidelines. The criteria help make guidelines that are actionable, are helpful to designers, are general enough to be applied to multiple product domains, and motivate the greenest alternatives. A mindmap method for consolidating the guidelines was also introduced. The final compilation of guidelines provides a reference that designers can expand and consult to curb environmental impacts from all stages of the life cycle.

In addition to providing a comprehensive set of green design guidelines and a technique for maintaining this set, this thesis proposes an original method for developing and creating new green design guidelines using reverse engineering, combined with a green requirements list and life cycle analysis. Previously, guidelines were created by reviewing literature, generalizing experience, or redesigning to satisfy metrics, such as disassembly time, that address impacts of only a single life cycle stage. The proposed method, however, fosters a more complete analysis of design concerns by combining customer needs, reverse engineering, green requirements, and life cycle analysis to discover guidelines.

A case study of electric kettles used the proposed method to discover four new guidelines and explore their environmental impact. Reverse engineering and an environmental checklist helped create a green requirements list. Experimentation measured the relevant design specification. The final requirements list, reverse engineering outcomes, and 6-3-5 concepts were used to formulate the new guidelines. Finally, each guideline was tested using an LCA of a representative redesign concept. Although all of the guidelines helped reduce net environmental impact, scenarios existed for which tradeoffs might outweigh the benefits of some guidelines. Some of the redesigns incorporated features that increased the number of components and therefore increased the environmental impact of manufacturing the kettle. Also, it was possible that the features would not be used and their manufacturing costs would increase the net life cycle impact. Existence of the guidelines in current energy saving products suggests that the guidelines are useful for multiple product domains. A study of these examples show that the guidelines do not always have significant, negative tradeoffs. Overall, the guidelines can reduce environmental impact in a diverse set of design problems.

A concept generation experiment provided additional evidence that the guidelines are useful in generating energy efficient concepts for products other than electric kettles.

Participants were asked to design an energy-efficient toaster. One group of participants was asked to use the guidelines as idea generators, while another was not given any idea generators. Resulting concepts were dissected into unique features and each feature was assessed for viability and environmental benefit. The results show that the participants with guidelines produced a greater number of green, viable features that the group without guidelines. Additionally, the group with guidelines explored more of the toaster's functions. Although the guidelines helped create more viable green features in this case study, a larger sample size is needed for establishing statistical significance.

The contributions of this thesis motivate future work to create more guidelines, ensure the usefulness of guidelines in design, explore the tradeoffs that occur when following guidelines and explore general techniques for estimating these tradeoffs.

6.2 Future Work

The work in the previous chapters led to more research questions and the need for further case studies. Results of the kettle case studies support further research of tradeoffs related to green design guidelines. A method or set of rules could be developed for overcoming conflicts. Additionally, the toaster study in Chapter 5 was not statistically conclusive. Future case studies should use larger samples, explore different problem statements and solicit industry participation to obtain stakeholder feedback.

6.2.1 Validating Existing Green Design Guidelines and Exploring Conditions of Tradeoffs

The most thorough means of understanding the effects of each guideline is to collect, create, and analyze life cycle comparisons of products that do and do not implement guidelines. It is possible that some guidelines only improve a product's environmental footprint in unique contexts, while others are more generally verifiable. A research study quantifying the impact of guidelines in finished products would help designers evaluate tradeoffs in new design projects.

Besides simply offering examples, such a study could also develop general rules mitigating negative tradeoffs. In the example of the kettles, energy reduction techniques were undermined by variability in consumer use. This example was a conflict between some of the new guidelines and an additional guideline for minimizing the number of components. It could be possible to link frequently conflicting guidelines as a checklist to remind designers to find a compromise between the guidelines.

Along with tools for identifying conflicting guidelines, further research could discover ways to resolve the conflicts and satisfying both guidelines. During the toaster case study, many designers sought to implement an existing guideline for fail-safes against heat loss in their toaster. However, they often sought to provide a fail-safe by adding components such as insulation. A couple of designers used a mirrored surface for the insides of their toasters instead. Mirrored surfaces would not increase the number of components and still follow the guideline to prevent heat-loss by reflecting radiative heat back towards the toast. Similar examples of overcoming conflicts in green design could be discovered and documented in a form useful to designers. The theory of inventive problem solving (TIPS) is a well-known set of innovative solutions to conflicts in design [78]. TIPS is the result of a larger study of patents and identified 40 principles for eliminating conflicts in design. It uses a matrix to identify solution principles that resolve conflicts between two specified design parameters. A similar construct could be devised for green design.

Further studies could also include conflicts between green design and other, common design requirements such as cost and safety. Brezet *et al.* have already presented a table of the conflicts and complements between eco-design principles and other design considerations (e.g. safety and cost) [32].

6.2.2 Exploring Part and Energy Synergy

Guideline D-32, “Interconnecting available flows of energy and materials within the product or between the product and its environment”, arose frequently in this research and motivates several potential design studies. Most products are designed to operate independently of other products. Synergy between products, such as a toilet and a sink, hold unexplored potential for sustainable innovation. Two potential areas of study are reuse of waste heat and component sharing.

Guideline D-32 could motivate design of a component that could store and transfer waste heat between products. Such a component might be transformable and incorporate phase change materials. Experimentation using prototypes could help identify the most promising product applications and revise the design. The resulting component could then be incorporated into future products.

Existing products share many similar components, such as batteries and motors. Dozens of products containing motors may exist in a single household. All of those products could be operated with a single, interchangeable motor. Interchangeable common components would reduce the need for duplicate manufacturing. Additionally, an efficiency upgrade to the shared component would not make the existing products obsolete. Instead, all products in a home would be upgraded simultaneously.

Conversely, a single common component might not be robust to the needs of a variety of components. The interfaces may require additional equipment, introduce opportunities for failure, and reduce quality of performance. Experimentation with these component sharing products and comparison with single products would reveal design flaws and unique failure modes. Further life cycle analysis of component-sharing alternatives would help estimate their environmental costs and benefits.

6.2.3 Developing Guidelines for More Products

The method for developing new green design guidelines has been applied to one aspect of product use and one product case study. While a single case study shows how a method might be useful, additional case studies should explore the method's usefulness in other product classes. Besides analyzing energy consumption during use, the method could be applied to other areas of product utilization. One possible application is designing products to have longer lifetimes and be more durable during use. Customer use and changing needs constitute an important analysis step of the method and have significant influence on a product's useful life.

Additionally, the usefulness of the method in a research setting may not reflect its usefulness in an industry setting. It would be helpful to cooperate with industry and teach the method to designers interested in creating green product lines. These partnership studies could not only test the usefulness of the method, but also elicit feedback for augmenting and improving the method.

6.2.4 Experiments on the Utility of Green Design Guidelines

The initial experiment of 10 participants designing energy efficient toasters revealed that a larger sample size would better support conclusions about the usefulness of guidelines. The application of the four guidelines to new toaster concepts was helpful and apparent, but not statistically significant. Future studies should test methods of presenting the guidelines and attempt to give designers the entire set of guidelines as a tool for new design. Industry participants could provide stakeholder feedback to refine the use of guidelines as a tool.

APPENDICES

Appendix A : Complete Set of Guidelines and Descriptions

A. Ensure sustainability of resources by: [2; 23; 25]

1. *Specifying renewable and abundant resources*

Select energy sources and materials that are plentiful, readily available and replenish at rates higher than their consumption. The goal is protect ecosystems by creating imbalance or scarcity of resources necessary to the ecosystems' health or our own quality of life.

Example: Bamboo has been replacing wood as a sustainable flooring material. Bamboo crops grow at much faster rates and with higher yields than wood forests making it a more renewable and abundant resource.

Caveat: Bamboo it is not altogether a greener resource; wood forests are, unfortunately, being replaced by bamboo crops. Additionally, some bamboo crops are being treated with more pesticides than required to increase yields further. Agricultural practices are very important to the sustainability of a resource. This aspect is addressed by principle B.

Sources*:* [4; 5; 8; 14; 25; 30]

2. *Specifying recyclable, or recycled materials, especially those within the company or for which a market exists or needs to be stimulated*

If recycling technology and industry are to advance, become profitable and more mainstream, the recycled product must first be in demand. Designers should try to design their concepts to make use of these recycled products. Opportunities for recycling material may exist within a company's own supply chain. These opportunities should be sought out to avoid intermediate and superfluous transportation steps.

Example: Global Zero, Inc. made their cassette plastics entirely out of polypropylene for easy injection molding with recycled materials. When they were looking to find a source of recycled polypropylene they worked with Discus, a plastic company, to create a recycled PP stock using left over trimmings from a nearby Kimberly-Clark diaper plant. Thereby, Global Zero obtained recycled PP and Kimberly-Clark could market their processing waste [79].

Sources: [1; 4; 5; 8; 10; 14; 23-25; 29; 31; 33]

3. *Layering recycled and virgin material where virgin material is necessary*

There are some cases where virgin material is necessary, such as food products. Even in cases requiring high material quality, it is possible to mix or layer virgin and recycled material to reduce the amount of material extraction involved in the product's life cycle.

Example: A water bottle is one example of product that requires high quality virgin material, but this requirement can still be met with higher recycled material content if the virgin material is used as a coating layer on top of recycled material.

Sources: [4; 5]

4. *Exploiting unique properties of recycled materials*

Recycling does not only provide material stock. Scrap, excess and waste material all have unique textures, color combinations, and intermixed patterns that can be used in aesthetic and functional design. A designer that takes advantage of these can forgo additional production steps, and divert valuable material from landfills with minimal reproduction.

Example: An example of not just recycled, but reused material comes from Bitters Co. They design doormats and key-chains using foam rubber salvaged from the excess of Flip Flop production. Re-using waste from the manufacturing stage, Bitters Co. maintains the original coloring to create patterns in their final doormat or key-chain, shown in Figure X.

Sources: [4,5]

5. Employing common and remanufactured components across models

By using common parts and remanufactured components, a designer ensures that those parts complete their useful lifetimes and avoids the unnecessary materials and manufacturing associated with additional virgin components. The designer may also create a product line that supports reuse by enabling interchangeable parts.

Example: The structure and modularity of the Rank-Xerox® photocopiers accommodate remanufactured modules, from current and previously introduced products. Each model contains remanufactured parts, such as paper trays, and common cartridges.

Sources: [5; 8; 14; 24; 29; 31]

6. *Specifying mutually compatible materials and fasteners for recycling*

To make recycling of products and components easier, it is preferable that all the materials are the same or can be processed together. This combination of compatible materials reduces the amount of contamination, separation and sorting and increases the likelihood of the resources being processed correctly.

Sources: [1; 4; 5; 8; 10; 14; 24; 29-31; 33]

7. *Specifying one type of material for the product and its subassemblies*

To make recycling of products and components easier, it is preferable that all the materials are the same. This combination of compatible materials eliminates contamination, separation and sorting and increases the likelihood of the resources being processed correctly.

Sources: [1; 4-6; 8; 23; 24; 27; 29; 31; 33]

B. Ensure healthy inputs and outputs by: [2; 27]

8. *Installing protection against release of pollutants and hazardous substances*

It is important that products are designed against leaking of chemicals, emitting pollutants, off gassing and transmission of harmful substances. A few techniques are additions such as leak protectors, state-of-the-art filtration, and enclosed, protected subsystems.

Sources: [4; 5]

9. *Specifying non-hazardous and otherwise environmentally "clean" substances, especially in regards to user health*

A large part of green design is to find new ways to use cleaner substances than are currently used. Biodegradable, non-toxic, and organic materials are just a few examples.

Sources: [1; 4; 5; 10; 14; 23-25; 29; 33]

10. Ensuring that wastes are water-based or biodegradable

When designing a product with waste that might return to the environment, through a landfill or the sewer system, it is desirable that this waste can be easily re-processed by the environment by being water-based or biodegradable.

Sources: [1; 8; 25; 31]

11. *Specifying the cleanest source of energy*

By using cleaner power and energy storage sources, such as solar power or rechargeable batters, a product can avoid effects of less clean energy sources, such as burned fuels. Directly harvesting solar thermal energy is often preferable to electrical heaters.

Example: The Seiko Kinetic® Auto Relay is powered by the kinetic energy of the wearer's movement, a readily available and clean energy source.

Sources: [4; 5; 25; 29]

12. *Including labels and instructions for safe handling of toxic materials*

Labels and instructions help ensure that toxic materials are processed properly during use, repair and end-of-life.

Sources: [1; 5; 6; 10; 14; 23; 24; 29]

13. *Specifying clean production processes for the product and in selection of components*

As much as possible, designers should create products so that they can be manufactured in the most environmentally friendly way possible. They should also select components and materials that have been mined, manufactured, and grown in sustainable ways.

Example: SolFocus CPV systems use optics and glass to concentrate solar power onto a small 1cm2 area. They claim that their design with glass instead of silicon uses common, high volume manufacturing techniques and yields the lowest carbon footprint of any solar technology.

Sources: [1; 5; 10; 31]

14. *Concentrating toxic elements for easy removal and treatment*

When a product must have hazardous materials, chemicals or components, it helps to keep track of and remove these for future use and processing if they are concentrated in designated areas of the product.

Sources: [17, 31, 32, 36, 37] [41]

C. Ensure minimum use of resources in production and transportation phases by: [24; 27]

15. *Replacing the functions and appeals of packaging through the product's design*

Packaging often serves two purposes, to protect a product and to sell a product. Sometimes products are enclosed in plastic packaging, labels, or boxes that they do not really need. A product could just be designed to be attractive and resilient for retail in an unpackaged form.

Example: Toothpaste is one example of a product that might already be designed with the ability to replace its packaging. Toothpaste tubes are already printed with most of the packaging advertisements. The boxes help only in stacking the shelves easily. If the tubes were designed into a new shape that easily stacked or stood on shelves, excessive boxes would not have to be manufactured by companies and tossed by consumers.

Sources: [4; 5]

16. *Employing folding, nesting or disassembly to distribute products in a compact state*

In their usable state, most products fill a large footprint or volume of space. Products should be designed to fit as many units as possible into a single shipment, and thereby lower the number of shipments and the effects of transportation.

Sources: [4; 5]

17. *Applying structural techniques and materials to minimize the total volume of material*

Rethink over-dimensioned and "one size fits all" solutions. Rather than increasing thickness or size, one should try to specify high strength materials as well as investigate sturdier and more compact geometries.

Example: The Black and Decker® Leaf Hog™ uses ribbing to minimize material cost and still maintain structural rigidity and internal part placements.

Sources: [1; 4; 5; 8; 10; 14; 23-25; 27; 30; 31; 33]

18. *Specifying lightweight materials and components*

The efficiency of transportation vehicles is often a function of load weight. By making products lighter, the load weight is decreased and efficiency of the vehicle is increased. To achieve lighter products and reduce transportation effects, one should try to specify lightweight materials and components as well as investigate sturdier and more compact geometries.

Sources: [4; 8; 14; 31]

19. *Specifying materials that do not require additional surface treatment or inks*

Surface treatments and inks often incur extra production steps and use of harmful chemicals. By specifying materials that do not require additional processing, designers avoid the extra harmful processing steps and effects.

Sources: [4; 5; 25]

20.*Structuring the product to avoid rejects and minimize material waste in production*

By following good design for manufacturing guidelines, a designer can reduce the number of waste products and the amount of waste material formed during manufacturing.

Sources: [4; 5; 30; 31]

21. *Minimizing the number of components*

Each component within a product has its own life cycle of environmental impacts. Eliminating components eliminates the material extraction, manufacturing and transportation processes that would have been required to create those components and bring them to the assembly plant.

Sources: [4; 5; 29; 31]

22. *Specifying materials with low-intensity production and agriculture*

The environmental impacts of growing, extracting, and processing different materials or crops differ. A designer can research the environmental impacts of these processes and choose the most environmentally friendly of the candidate materials for a design.

Sources: [4; 14]

23. *Specifying clean, high-efficiency production processes*

When designing a part for manufacture, an engineer may have the opportunity to design their product for a special manufacturing process, choose between two or more production processes or create special manufacture instructions. Environmental friendliness and efficiency of the processes should be a major factor in production decisions with regards to design.

Sources: [1; 4; 14; 25; 31]

24. *Employing as few manufacturing steps as possible*

It is likely that the environmental impact of a product will be lower if there are fewer manufacturing steps. Usually, fewer steps require less energy, less chemicals, and have fewer opportunities for waste and transportation.

Caveat: Not all manufacturing steps or processes are the same. Multiple low-impact manufacturing steps could be preferable to one high impact step.

Sources: [37]

D. Ensure efficiency of resources during use by: [2; 23; 25]

25. *Implementing reusable supplies or ensuring the maximum usefulness of consumables*

Products that employ consumable supplies, like disposable filters or containers, often incur considerable environmental impact during their use stage because each consumable must be manufactured, cleaned with chemicals, packaged, transported and disposed. In order to minimize these impacts, designers should seek to reduce the number of consumables used if not eliminate consumables all together.

Example: Some instances of reusable supplies might be as simple as refilled plastic water bottles or glass milk jugs. Using reusable coffee filters rather than paper coffee filters is one common example of a reusable supply replacing a consumable.

Duplex printing is an example of how usefulness of consumables can be increased because duplex printing decreases the number of sheets used while increasing the content per sheet.

Sources: [4; 5; 15; 25; 31]

26.*Implementing fail-safes against heat and material loss*

Sustainable design aims to use the fewest resources possible to achieve a desired product performance. Two ways of achieving this goal are to conserve and to increase efficiency. One way of increasing efficiency is to decrease losses of resources during operation. Loss of energy normally occurs as heat transfer and material loss might occur as leaks or wear.

Example: Some fail safes might include increasing insulation, leak monitoring, minimizing surface area or creating better seals.

Caveat: here

Sources: [4; 5; 10; 15; 29]

27. *Minimizing the volume and weight of parts and materials to which energy is transferred*

One way of conserving energy or requiring less energy for operation is to reduce the mass or volume of parts and materials that energy is being transferred to. The larger the body, the more energy that body requires performing a certain task.

Example: In the case of heating water, making sure that only the necessary water is heated decreases the duration of heating, decreases heat loss, and significantly reduces net energy use.

Sources: [4; 5; 15; 29]

28.*Specifying best-in-class energy efficiency components*

Efficiency of a product is a product of the efficiency of its components. Increasing the efficiency of a single component can have a large impact on the overall transmission of energy.

Sources: [4; 5; 10; 14; 15; 29]

29.*Implementing default power down for subsystems that are not in use*

If a subsystem requires energy to operate, that subsystem should only be receiving energy while in use. If a subsystem is not in use or is not needed, but is using energy to remain active, that energy might be wasted.

Example: Examples include shutting off monitor displays after computer inaction or using sleep modes. A larger example might be rooms with lights that shut off automatically so that only occupied rooms use power for lighting.

Caveat: In some example, cycling between on and off states can decrease product lifetime or use more energy that simply remaining on. Best judgment should be considered when applying this guideline.

Sources: [4; 5; 25; 29]

30. *Ensuring rapid warm up and power down*

Designing systems to reach full operation in a shorter amount of time while using the same or similar power levels can reduce the next energy use for power up and power down.

Example: An example might be a projector that uses a fan to cool down the bulb and system for a long length of time before shutting off. If the heat transfer and fan were more efficiency at removing heat, the length of time and overall energy use could be decreased.

Caveat: This guidelines applies on a case-by-case basis. Not all systems use a lot of energy to power up or down and it is possible that a system will use less energy by gradually reaching full operation if faster starts or shut downs.

Sources: [15]

31. *Maximizing system efficiency for an entire range of real world conditions*

Designers should strive to account for normal and possible aberrations in use when designing their systems. Products are not usually used exactly as intended. Designing systems for a single use mode may yield lower efficiencies in the actual, variable use modes of the product. Considering efficiencies for a range of use modes might allow designers to locate other operating parameters with uniformly better performance efficiency.

Example: here

Caveat: here

Sources: [4; 15; 23]

32. *Interconnecting available flows of energy and materials within the product or between the product and its environment*

Every product has energy and material inputs and outputs. Many products have opportunities for synergy by matching material outputs of one product with material inputs of another product. One product's waste could become another product's feedstock. Additionally, products could share batteries, power supplies, or components to reduce lifecycle resource use.

Example: Regenerative braking recovers expended energy. Instead of braking a car by disk or drum brakes and losing kinetic energy as heat, the electric generator is reversed from powering the wheels to being powered by, and effectively slowing, the wheels.

Sources: [2; 23]

33. *Incorporating part-load operation and permitting users to turn off systems in part or whole*

Sometimes systems are offered with features that consumers either do not need or do not want. By allowing products to be operated with or without these features by making them optional, these products can reduce energy or resources waste on operating these additional features.

Sources: [4; 5; 23; 29]

34. *Use feedback mechanisms to indicate how much energy or water is being consumed*

Energy and water are both valuable resources that users often waste because of ignorance. By incorporating mechanisms that allow users to measure how much energy or water they want to use or monitor how much energy or water they are using, consumers can become more actively involved and pro-active in conserving. They may be motivated to use products more appropriately or even test new habits to see what level of savings they can achieve on their own.

Example: The Toyota Prius offers a power and mpg monitoring display. Users can see how much energy they are recovering using regenerative breaking and how their driving habits affect their gas mileage. Many users enjoy this feature and turn it into a challenge to modify their habits and achieve better performance than other drivers.

Sources: [14; 25]

35.*Incorporating intuitive controls for resource-saving features*

Resource-saving features, such as energy monitoring, energy metering, and partial load operation, are more likely to be used more frequently if their operation is intuitive to the user. The easier a feature is to master, the more effective that feature will become.

Sources: [14; 15]

36. *Incorporating features that prevent waste of materials by the user*

Users often waste materials by improperly using products, accidentally contaminating, overflowing, or spilling materials. Designers should try to foresee accidents or misuse that might occur during operations and incorporate features that guide the user's interactions with a product and materials.

Example: A simple example is a funnel to aid pouring and prevent spills.

Sources: [4; 5]

37. *Defaulting mechanisms to automatically reset the product to its most efficient setting*

Users may not always know to operate a product at its most efficient setting. Products that must be manually set to less efficient settings and return to their most efficient settings are more likely to save energy or materials that would be wasted on less efficient or less appropriate settings.

Example: One example would be dishwashers that set the heated dry cycle to off after every cycle. This automatic default would require that the user manually turn on heated dry whenever they desire it. Dishes waste less electricity by air-drying and consumers only require the heated dry if they do not want to towel dry and need the dishes immediately. As another example, the eco-kettle tries to limit the amount of water heater by having separate storage and heating compartments. Users encounter resistance when pushing the button that allows water to travel from one compartment to another compartment. The default of this system is to keep water in the storage compartment.

Sources: [17]

E. Ensure appropriate durability of the product and components by: [2; 10; 25; 27; 31]

38. *Reutilizing high-embedded energy components*

Though a product or parts of its systems may become obsolete or break, many other components can operate for much longer lifetimes. Components that require more intensive manufacturing process and contain more valuable materials should be reused rather than replaced. These can be reused in the replacement product so that a new component does not need to be manufactured. Companies could also collect old components and remanufacture them for new products.

Sources: [2]

39. *Planning for on-going efficiency improvements*

Sometimes only a small number of the components or systems in a product need to be updated to experience efficiency gains. Designers should try to foresee possible upgrades and design the product architecture and systems to allow for part replacement and system upgrade.

Sources: [10; 23]

40. *Improving aesthetics and functionality to ensure the aesthetic life is equal to the technical life*

Sometimes consumers replace products for aesthetic reasons before the technology is outdated or broken. Making a product with sleek, timeless aesthetic qualities can have the product last longer. In addition, products with changeable shells and options for updating aesthetic or industrial design features could have extended useful lives.

Sources: [1; 4; 5; 10; 25]

41. *Ensuring minimal maintenance and minimizing failure modes in the product and its components*

Another way to increase the durability of a product is to design the parts for minimal wear and managing failure modes so that any maintenance required is trivial rather than debilitating.

Sources: [1; 5; 8; 14; 23; 24]

42. *Specifying better materials, surface treatments, or structural arrangements to protect products from dirt, corrosion, and wear*

Designers should take steps to ensure the longest life of products by using materials, surface treatments, and coverings that are appropriate for the types of wear and environmental contamination that product's might experience.

Sources: [27; 30]

43. *Indicating on the product which parts are to be cleaned/maintained in a specific way*

Providing instructions or clues as to proper maintenance on the product can help ensure that products are cleaned properly and not mishandled or damaged because of improper care.

Sources: [4; 5]

44. *Making wear detectable*

Easily detectable wear aids in repair and maintenance.

Example: Some examples would be materials that changed color with surface wear or coatings that disappear.

Sources: [4; 5; 30]

45. *Allowing easy repair and upgrading, especially for components that experience rapid change*

If parts or components become obsolete either in efficiency or features, they will need to be replaced. Products that cannot easily be repaired or upgraded often are thrown out when only a small part of the product is broken. By making products upgradeable, either by modularity or some other technique, the impact of changes in technology and customer needs are lower.

Example: Desktop computers are easily repaired and upgraded. Components can be swapped and upgraded almost indefinitely. Processors may be replaced every couple of years, but towers can last decades.

Sources: [27; 30]

46. *Requiring few service and inspection tools*

Reducing the number of tools needed to service products decreases the time spent on servicing, increases the ease or simplicity of servicing, and increases the likelihood that a product will be serviced.

Sources: [30]

47. *Facilitating testing of components*

Troubleshooting is a useful diagnostic method for determining causes for error or failures in products. A product could incorporate ways to visually inspect or test components individually so that product issues can be resolved more effectively.

Sources: [30]

48. *Allowing for repetitive dis- and re- assembly*

A product that requires frequent servicing or upgrading will most likely require frequent dis- and re- assembly. Such frequent operations may cause fatigue and wear on joints and cause interior organization to become disorganized. Planning the joints and interior of a product to be unaffected by frequent disassembly can prevent failures or mishaps.

Sources: [15]

F. Enable disassembly, separation, and purification by: [2]

49. *Indicating on the product how it should be opened and make access points obvious*

Disassembly is aided by reducing the time and effort required. By providing orientation arrows and making connections visible, designers aid workers in disassembling products. The parts are then more likely to be separated properly and recycled or reused.

Sources: [4; 5; 25; 29; 33]

50. *Ensuring that joints and fasteners are easily accessible*

Disassembly is aided by reducing the time and effort required. Easily accessible joints and fasteners improve the probability that a product can be disassembled and recycled cost effectively.

Sources: [24; 29; 33]

51. *Maintaining stability and part placement during disassembly*

When disassembling products, parts can become damaged or lost if they fall or relocate. Internal architecture should ensure that part placement is secure during disassembly to prevent mishaps and ensure that reusable parts are not damaged and workers are not injured.

Sources: [29; 30]

52. *Minimizing the # and variety of joining elements*

The more joining elements a product has, the more operations need to be carried out before it is recycled. Different joining elements may require additional set up time for tools or work stations. By reducing the number and variety of joining elements, the disassembly process becomes more straightforward and less complicated making it shorter and more cost effective.

Sources: [5; 6; 24; 27; 29; 31; 33]

53. *Ensuring that destructive disassembly techniques do not harm people or reusable components*

Processes that break product shells or fastener can damage other parts if those parts experience impact or temperature changes. Some processes might even result in projectiles or other work hazards. When implementing destructive disassembly techniques is necessary, ensure that they do not affect people or parts, either by selection of the appropriate technique or by placement of components.

Sources: [24; 29; 30]

54. *Ensuring reusable parts can be cleaned easily and without damage*

Some parts are reusable in new products and may need basic maintenance like cleaning. Design of these parts should ensure that cleaning processes will not come in contact with smaller, internal components that might be damaged.

Sources: [30]

55. *Ensuring that incompatible materials are easily separated*

Certain materials cannot be recycled together. If a design requires that two materials that are incompatible for recycling be co-joined, then the design should also allow for the materials to be easily separated, preferably by hand, at end of life so that recycling streams do not become contaminated or that the recycled material is not thrown away because of the incompatible element.

Sources: [5; 8; 14; 24; 29]

56. *Making component interfaces simple and reversibly separable*

In general, it is helpful for recycling and reuse if all components that are valuable individually be joined and separated easily. The more complicated the interface, the more likely a contact is to be damaged. Additionally, more complicated interfaces might make separation process seem to incur more cost than benefit.

Sources: [4-6; 8; 14; 24; 29]

57. *Organizing in hierarchical modules by aesthetic, repair, and end-of-life protocol*

If designers can discern in what order or importance aesthetic changes, disassembly or servicing might take place, then designers should organize modules associated with each task so that there are no conflicts. For example, if a component cannot be removed without permanently damaging a product, then other removable components should not be located behind that component.

Sources: [4; 5; 8; 10; 14; 24; 25; 29-31; 33]

58. *Implementing reusable/swappable platforms, modules, and components*

There are many opportunities for reusing product casings or certain common components or subsystems. Designers should consider using available lines of or creating new lines of reusable platforms and remanufacturable components or modules.

Example: Kodak one-use cameras have reusable product platforms and shells so that after a customer returns a camera to have the film developed, the camera platform can simply be updated with new markings and internal components before returning to retail.

Sources: [1; 8; 10; 14; 24; 29; 30]

59. *Condensing into a minimal # of parts*

Products with fewer parts such as levers, motors, joints, and pins can be simpler and require less material. They may also require fewer manufacturing processes and assembly steps as well.

Caveat: Sometimes condensing parts makes them wear more quickly or eliminates interfaces, reducing the ability to disassemble, separate and upgrade products.

Sources: [1; 5; 8; 14; 23-25; 29]

60. *Specifying compatible adhesives, labels, surface coatings, pigments, etc. which do not interfere with cleaning*

Sometimes labels, adhesives or other coatings on products can be difficult to clean and require strong harmful chemicals for cleaning. Some pigments or aesthetics may also be destroyed during cleaning. Necessary surface treatments to products should be resistant to cleaning during useful life, but cleaned easily with more biodegradable chemicals at end of life.

Sources: [4-6; 8; 14; 24; 25; 29; 31; 33]

61. *Employing one disassembly direction without reorientation*

A product is more likely to be disassembled and recycled if it can be placed on a disassembly line and completely separated into its constituent parts without further management in orientation.

Sources: [4; 5; 29; 31]

62. *Specifying all joints so that they are separable by hand or only a few, simple tools*

The number and complexity of tools required to disassemble a product increases disassembly cost and time. By making products separable by hand and only a few, simple tools, the cost and time of disassembly is reduced and therefore disassembly of the product for recycling and reuse is more likely.

Sources: [4; 5; 24; 29; 31]

63. *Minimizing the number and length of operations for detachment*

By making disassembly operations as few and as short as possible, the cost and time of disassembly is reduced and therefore disassembly of the product for recycling and reuse is more likely.

Sources: [29; 31]

64. *Marking materials in moulds with types and reutilization protocol*

Many materials need to be recycled separately and some require special instructions. Recyclable materials that are not marked with these instructions usually get land filled.

Sources: [1; 4; 6; 14; 23; 25; 29-31; 33]

65. *Using a shallow or open structure for easy access to subassemblies*

More shallow and open product structures make it easier to access and remove components without interference.

Sources: [17]

Appendix B : Results of Kettle Analysis and Experiments

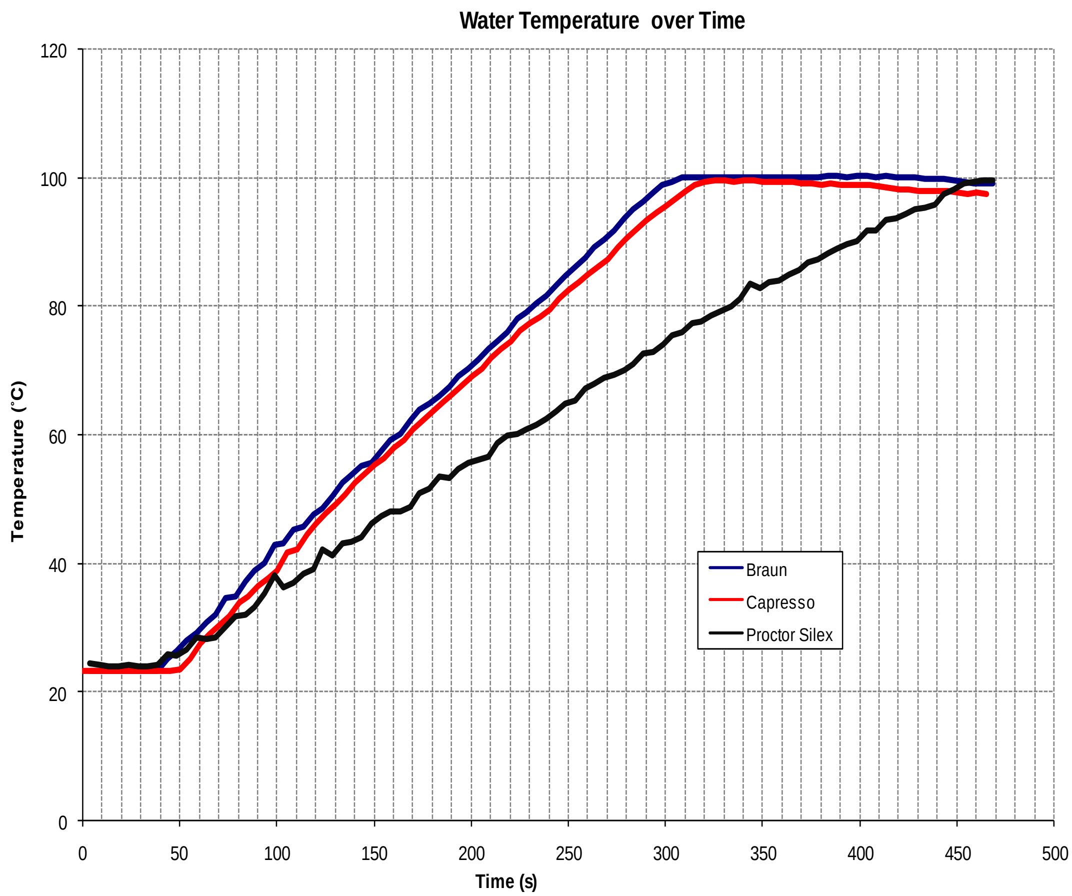


Figure B-1: The Measured Temperature of Three Mugs of Water Inside the Kettles Before, During, and After Heating

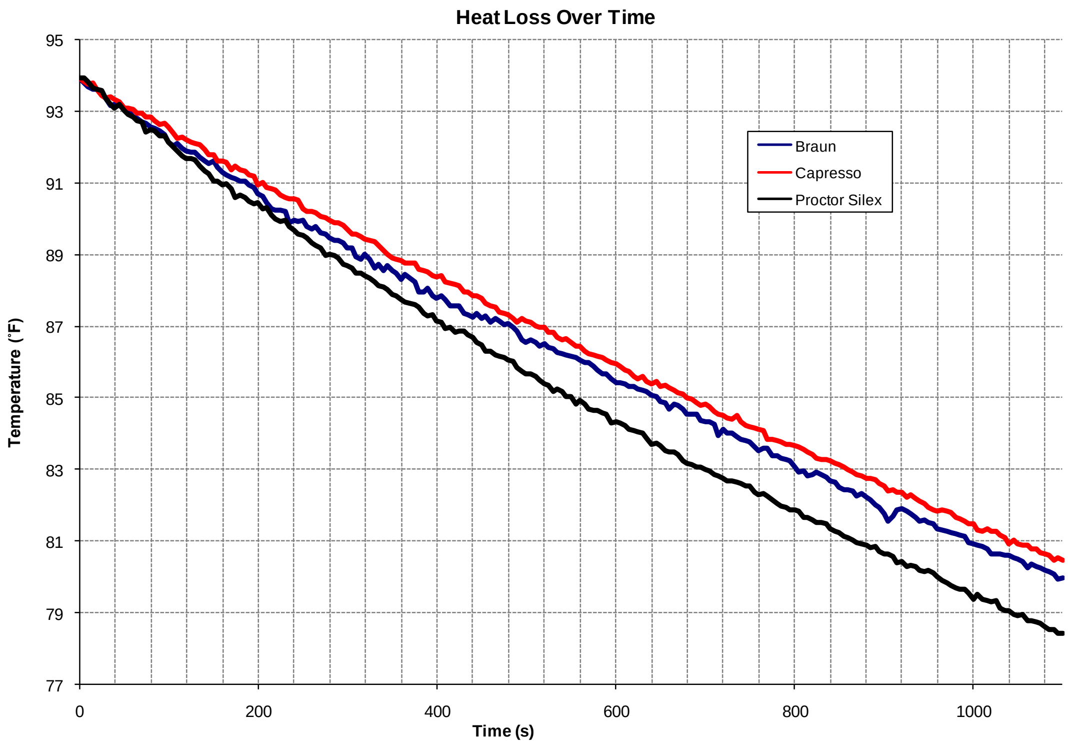


Figure B-2: The Cooling Profiles for the Three Kettles with Three Mugs of Water Inside Indicate Insignificant Insulation Differences

LEGEND	
Very Good	green
Could be better	yellow
Partial/Opportunity	orange
Violates	red
N/A	white

Principle	Guideline	ProctorSilex Kettle	Braun Kettle	Capresso Kettle
Sustainable Resources	9. Specifying renewable forms of energy	Subject to Grid sources	Subject to Grid sources	Subject to Grid sources
Cleaner Resources	13. Specifying the cleanest source of energy	Subject to Grid sources; Resistive heat?	Subject to Grid sources; Resistive heat?	Subject to Grid sources; Resistive heat?
Use Phase	28. Implementing fail safes against heat and material loss (or gain)	Spout design? Lid. Inner coils.	Spout design? Lid. Inner coils.	Spout design? Lid. Inner coils.
	29. Minimizing the volume and weight of parts and materials to which energy is transferred	Unknown	Unknown	Unknown
	30. Specifying best in class energy efficiency components	Resistive Heater	Resistive Heater	Resistive Heater
	31. Implementing default power down for subsystems that are not in use	Auto-Shut Off	Auto-Shut Off	Auto-Shut Off
	32. Minimizing standby power consumption	Unknown	Unknown	Unknown
	33. Ensuring rapid warm up and power down	Near instantaneous	Near instantaneous	Near instantaneous
	34. Maximizing system efficiency for an entire range of real world conditions	Unknown	Unknown	Unknown
	35. Interconnecting available flows of energy and materials within the product and its environment	N/A	N/A	N/A
	36. Incorporating part-load operation and permitting users to turn off systems in part or whole	N/A	N/A	N/A
	37. Use feedback mechanisms to indicate how much energy or material is being consumed	Measures Water	Measures Water	Measures Water
	38. Incorporating intuitive controls for resource saving features	Measures Water	Measures Water	Measures Water
	39. Incorporating features that prevent waste of materials by the user	Measures Water	Measures Water	Measures Water
	40. Defaulting mechanisms to automatically reset the product to its most efficient setting	Probably Doesn't	Probably Doesn't	Probably Doesn't

Figure B-3: Comparison of the Kettle Design and Current Energy Principles

Appendix C : Kettle Exploded Views and Bills of Materials

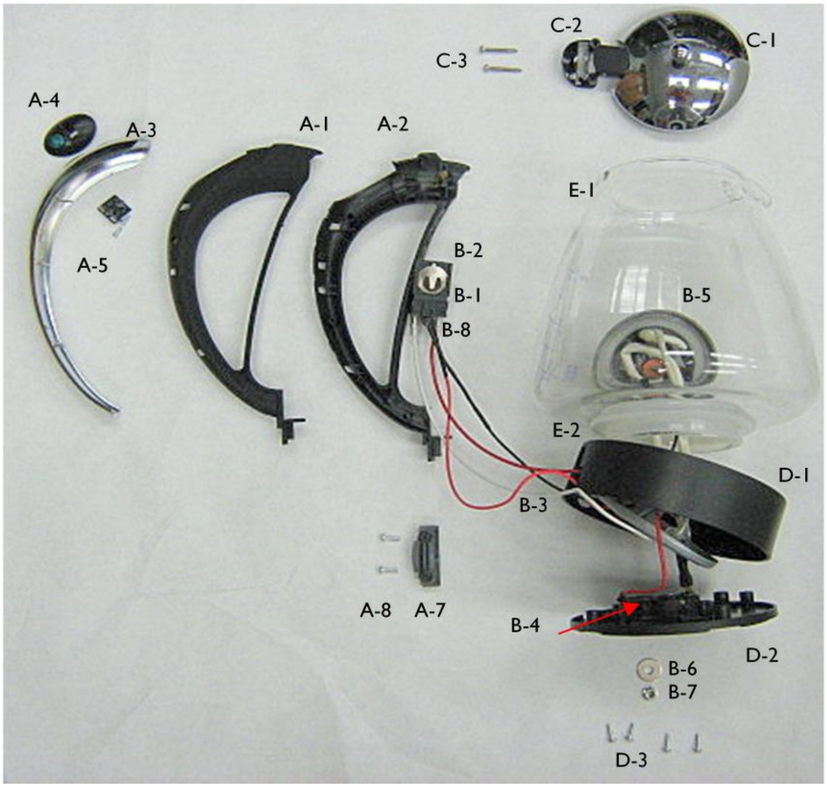


Figure C-1: Capresso Exploded View (Correlated with BOM)

Bill of Materials: Capresso Electric Kettle

Module/ Part #	Description/Name	Qty	Function	Mfg. Process	Dimensions	Mass	Material
A: Handle							
A-1	Side Shell Left	1	Enclose/Import Human	Injection Molded	Thickness = 3mm ID=10-29mm	25g	Polyamide
A-2	Side Shell Right	1	Enclose/Import Human	Injection Molded	Thickness = 3mm IDmax=10-29mm	25g	Polyamide
A-3	Shell Cover	1	Enclose/Import Human	Injection Molded	Width=21-34mm ID=19-33mm Thick=1mm	20g	Polyamide
A-4	Switch Top	1	On/Off	Injection Molded	LongD=37mm WideD=25mm Thick=7mm	<5g	Polyamide
A-5	Switch Bottom	1	Hold Switch	Injection Molded	Width =16mm Length=16mm Height=4mm	<5g	Polyamide
A-6	Switch Screws	2	Connect A-4&5	Cold Headed / Thread Rolled	length = 9mm thread diam = 3mm	<5g	Steel
A-7	Bottom Fixture	1	Connect to Base	Injection Molded	Width =39mm Length=11mm Height=12mm	<5g	Polyamide
A-8	Bottom Screws	2	Connect to Base	Cold Headed / Thread Rolled	length = 20mm thread diam = 3mm	<5g	Steel
B: Electronics							
Diam =	Switch	1	Regulate EE	OEM	Length = 37mm Width=22mm Height = 13mm	5g	OEM
B-2	Bi-Metal	1	Actuate Switch	OEM	Diam = 18mm	<5g	OEM
B-3	Wires	5	Transport EE	Rolled	Length=350mm WireGage=16A T=200Celcius V=300V	<5g	Copper
B-4	Electric Contacts	3	Import EE	Stamped / Rolled	Tabs=28mmLX5 mmW Prong=11mmLX2 mmOD	<5g	Copper alloy?
B-5	Resistive Heating Element	1	Conver EE to TE	Bending	Length = 60mm Diam = 7mm	170g	Stainless Steel Dome/Ceramic or Iron Element
B-6	Washer	1	Fasten	Machined / Stamped	OD = 15mm ID = 5mm	<5g	Steel
B-7	Nut	1	Fasten	Forged	ID = 3.5mm	<5g	Steel
B-8	LED	1	Signal On	OEM	OD = 5mm		OEM
C: Lid							
C-1/C-2	Lid Top/Bottom	1	Stop Steam	Injection Molded	Diam = 84mm	35g	Polyamide
C-3	Hinge	1	Rotate	Injection Molded	Width = 33mm Thick = 5 mm Length = 22mm	<5g	Polyamide/Steel Pin
C-4	Screws	2	Fasten	Cold Headed / Thread Rolled	length = 9mm thread diam = 3mm	<5g	Steel
D: Base							
D-1	Enclosure	1	Enclose EE Assembly, Support Kettled	Injection Molded	Height = 34mm OD = 12cm ID = 5cm	90g	Polyamide
D-2	Cap	1	Interface with Stand	Injection Molded	Diam = 1.5cm	45g	Polyamide
D-3	Screws	4	Fasten	Cold Headed / Thread Rolled	length = 9mm thread diam = 3mm	<5g	Steel
E: Body							
E-1	Kettle Enclosure	1	Reveal Water Height, Insulate/Hold Water	Blow Mold	Depth =14cm Width =14cm	345g	SCHOTT Heat Resistant Glass
E-2	Seal	1	Separate Water and EE Assembly	Transfer Molding	Thick = 2mm	170g	Rubber

Figure C-2: Capresso Bill of Materials

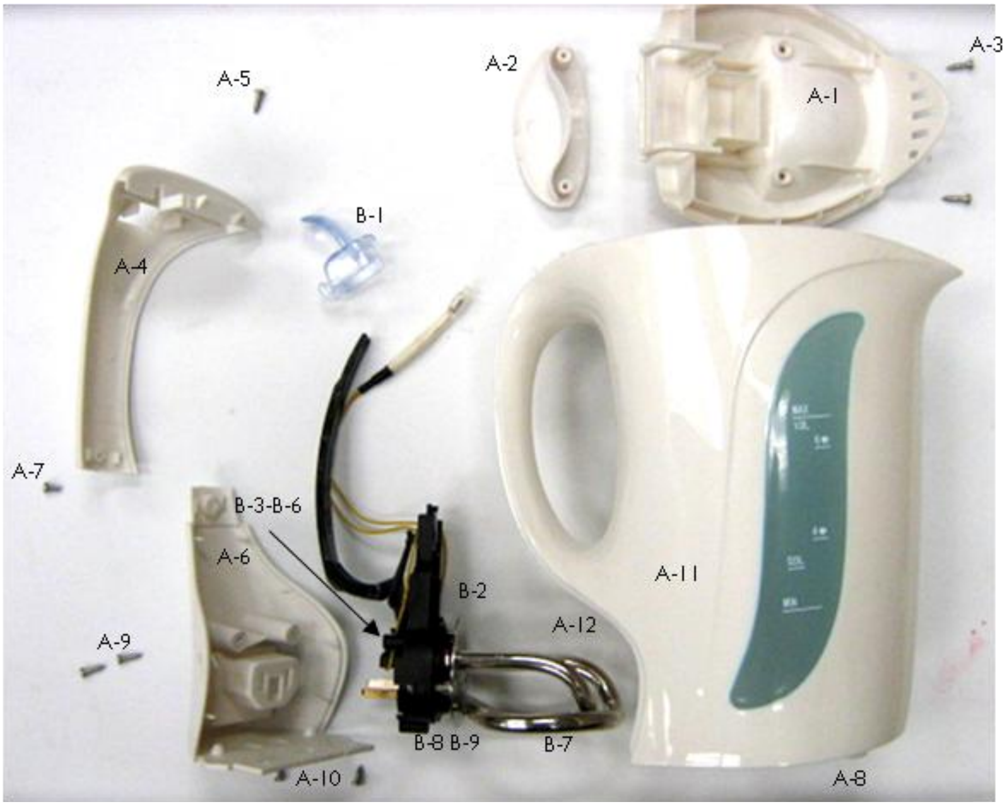


Figure C-3: Proctor Silex Exploded View

Bill of Materials: Proctor Silex Kettle

Module/ Part #	Description	Qty	Function	Dimensions	Material	Mass	MFG
A: Casing						357	
A-1	Lid	1			5 PP	40 g	PP Inj. Mould Part (GaBi)
A-2	Lid Handle	1			5 PP	5 g	PP Inj. Mould Part (GaBi)
A-3	Lid Screws	2	Connect A-1 to A-2	Philips Head	Steel	1 g	Steel Billet (GaBi)
A-4	Upper Handle	1	Import Hand, Stop Debris		5 PP	15 g	PP Inj. Mould Part (GaBi)
A-5	Upper Handle Screws	2	Connect A-4 to A-11		Steel	1 g	Steel Billet (GaBi)
A-6	Lower Handle	1	Import Hand, Stop Debris		5 PP	35 g	PP Inj. Mould Part (GaBi)
A-7	Handle Screw	1	Connect A-4 to A-6	Philips Head	Steel	1 g	
A-8	Rubber Plugs	2	Import Surface		Rubber	1 g	
A-9	Lower Handle Electric Screws	2			Steel	1 g	Steel Billet (GaBi)
A-10	Lower Handle Screws	2			Steel	1 g	Steel Billet (GaBi)
A-11	Body	1		Volume of Water: 4.75" tall, 4"Diameter = 59.7 Cubic Inches	5 PP	255 g	PP Inj. Mould Part (GaBi)
A-12	Rubber Seal	1	Stop Water (from leak from B-7 to B-2)		Rubber	1 g	Rubber Part Production (GaBi)
B: Regulatory and Electrical System						236	
B-1	Clear Switch	1			5 PP	1 g	PP Inj. Mould Part (GaBi)
B-2	Switch Lever and Electrical Assembly	1			5 PP, Steel, Copper, Aluminum	40 g	PP Inj. Mould Part(35g) + Steel Billet (GaBi) + Circuit Board (SimaPro)
B-3	Conducting Screws	3			Steel	1 g	Steel Billet (GaBi)
B-4	Thermal Washers	2			unknown	1 g	
B-5	Metal Washer	1			Steel	1 g	Steel Billet (GaBi)
B-6	Metal Frictional Washer	1			Steel	1 g	Steel Billet (GaBi)
B-7	Resistive Coil	1			Steel (cooper, nichrome, ceramic)	100 g	Steel Billet (GaBi)
B-8	Thermal Grease	1				dab	
B-9	Metal Plate	1	Attachs to A-11 under B-7	1-3/4" X 1-1/2"	Steel	1 g	Steel Billet (GaBi)
B-10	Electrical Cord	1	25 " long		Copper, Rubber	90 g	Rubber Part Production (GaBi)

Figure C-4: Proctor Silex BOM

Appendix D : Life Cycle Analysis Flows

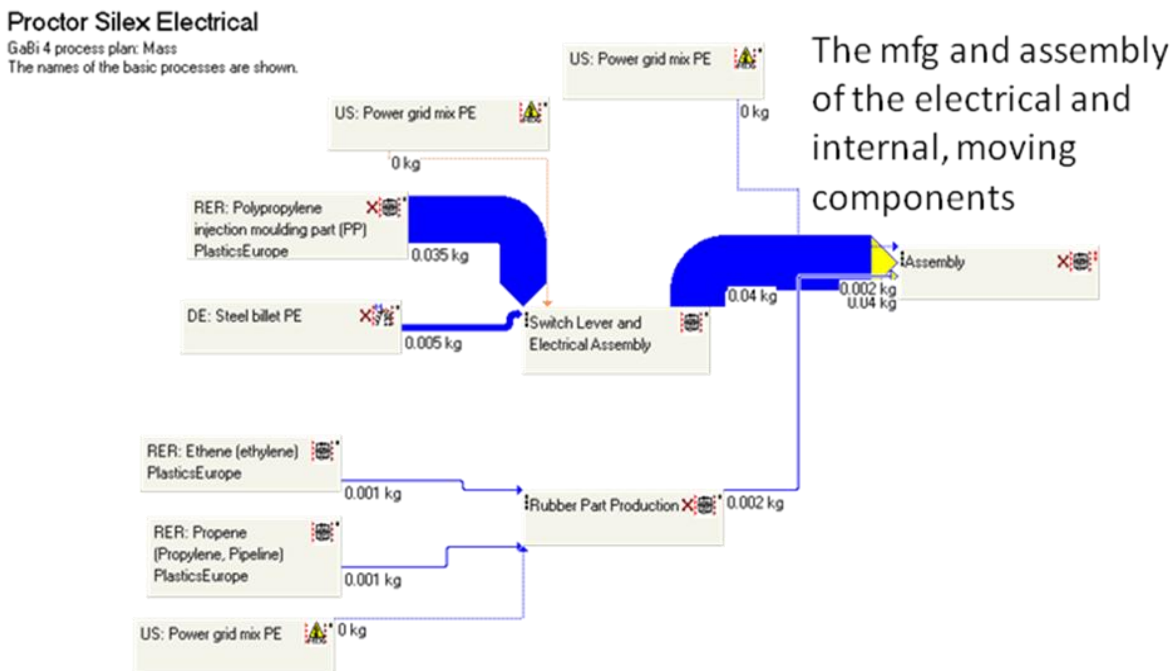


Figure D-1: Creating Electrical Components - GABI Flows

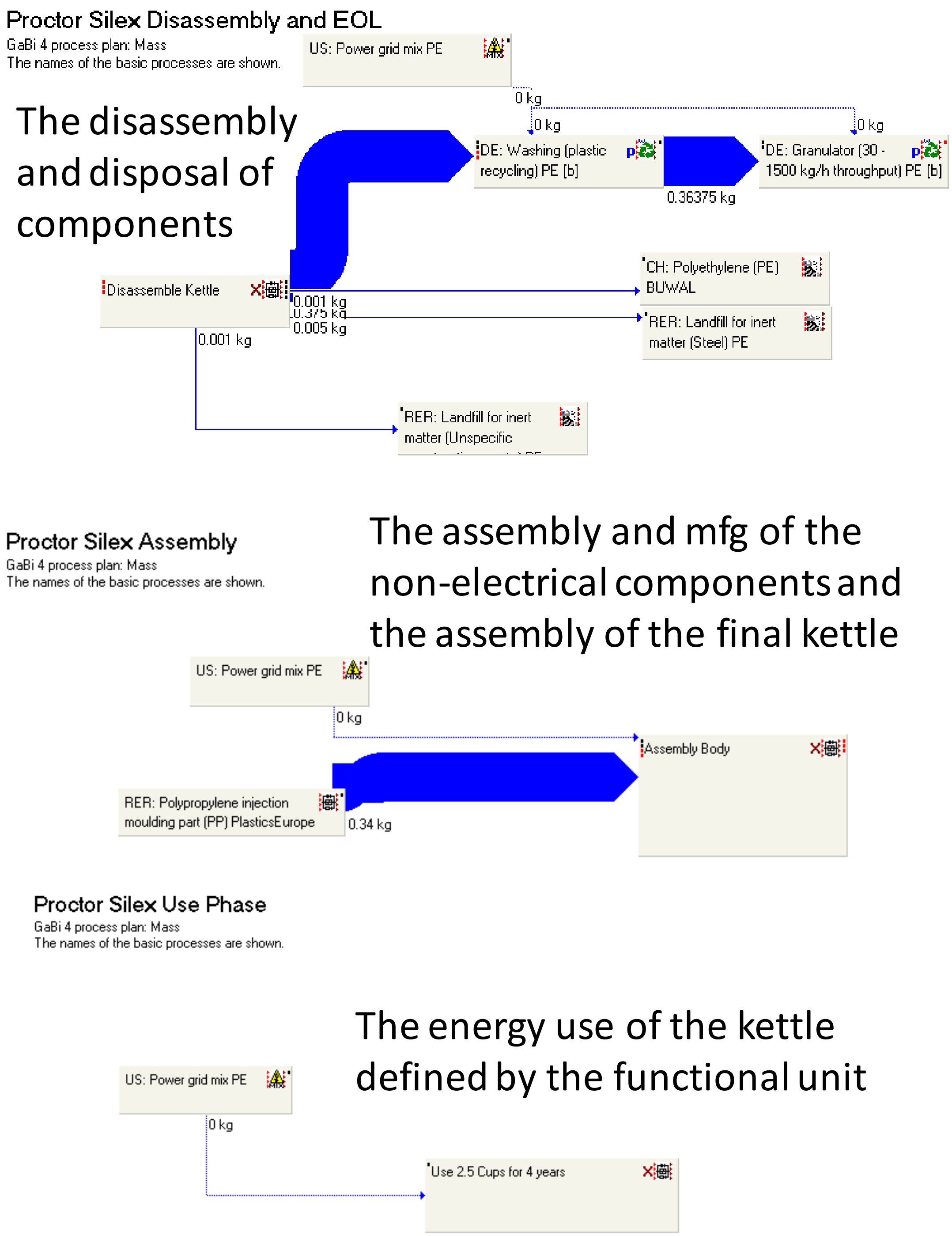


Figure D-2: Material and Energy Flows in GABI

Appendix E : Generated Kettle Concepts

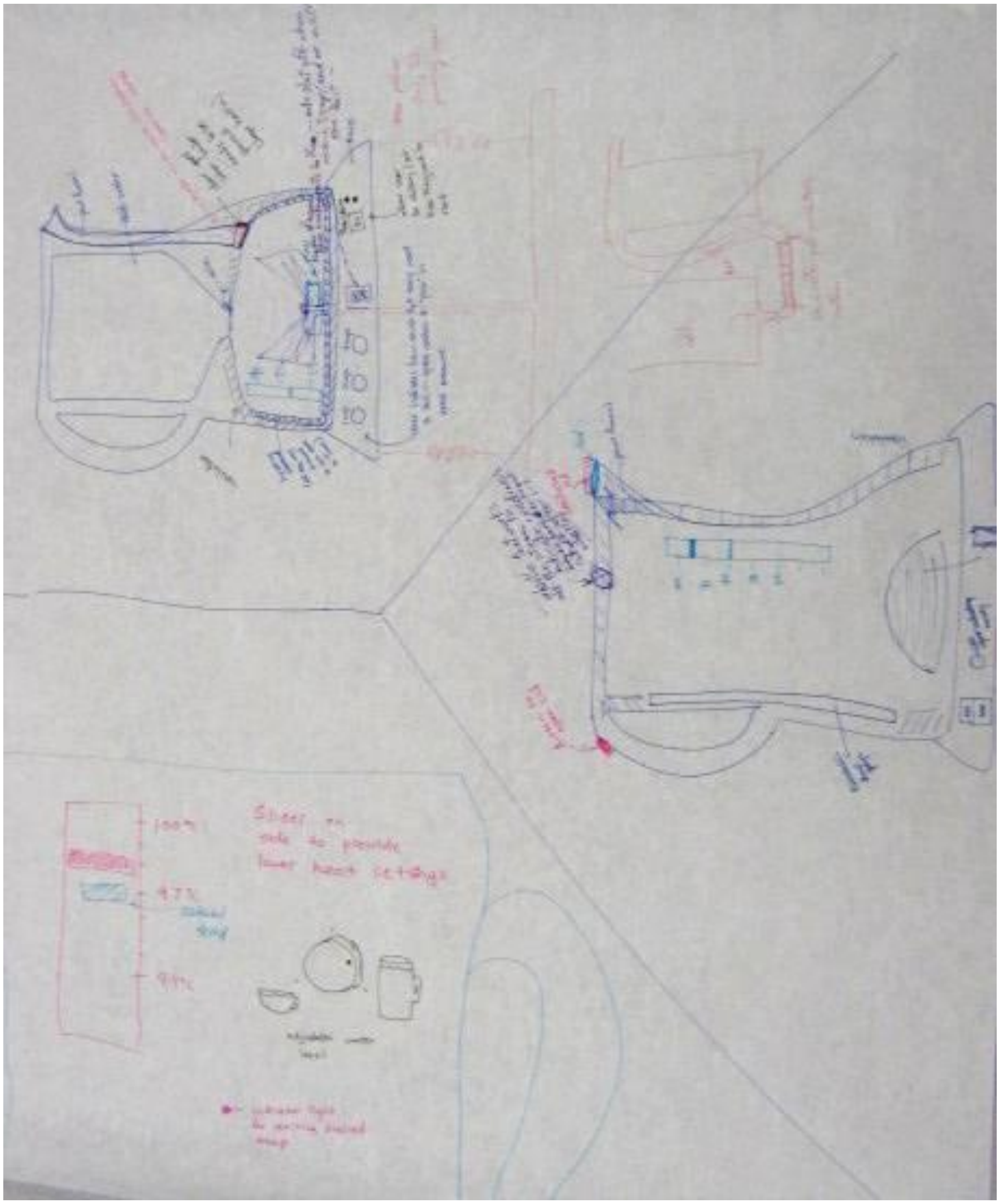


Figure E-1: Final Sheet from 6-3-5 Kettle Redesign

Appendix F : Data for Determining Energy Use of Redesign Concepts

Table F-1 Data Collected Simulating Kettle Improvements for Guidelines 1 and 2

		1	2
		Optimizing the time and rate of resource use for net minimization.	Incorporating automatic or manual tuning capabilities.
Design Change	Original Design	Earlier Shut Off	Set Shut Off Temperature
Shut off Temp (C)	100	95	76-100
Temperature Change (K)	75	73	52
Electricity In (W)	926	926	926
Heating Time (s)	360	304	183
Energy In (J)	333	282	169
Energy Absorbed (J)	217	211	150
Efficiency (%)	65	75	89
Energy Saved (J)	0	52	164

Table F-2: Benchmark for Overheating and Simulated Energy Savings by Redesign for Guidelines 3 and 4

		3		4
		Using feedback mechanisms to inform the user of current status of the process.		Creating separate modules for tasks w/conflicting requirements/solutions.
Design Change	Original Design	Temperature Screen		Separate Cup
Shut off Temp (C)	Reheat from 67 degrees	67-83	Shut off Temp (C)	100
Temperature Change (K)	33	16	Temperature Change (K)	75
Electricity In(W)	926	926	Electricity In(W)	926
Heating Time (s)	209	169	Heating Time (s)	360
Energy In (kJ)	194	156	Energy In (J)	333360
Energy Absorbed (kJ)	95	46	Energy Lost From Window (kJ/m^2)	1000
Efficiency (%)	49	30	Window Area (m^2)	0.002
Energy Saved (kJ)	0	37	Energy Saved (kJ)	2

Appendix G : Guidelines Group's Toaster Concepts

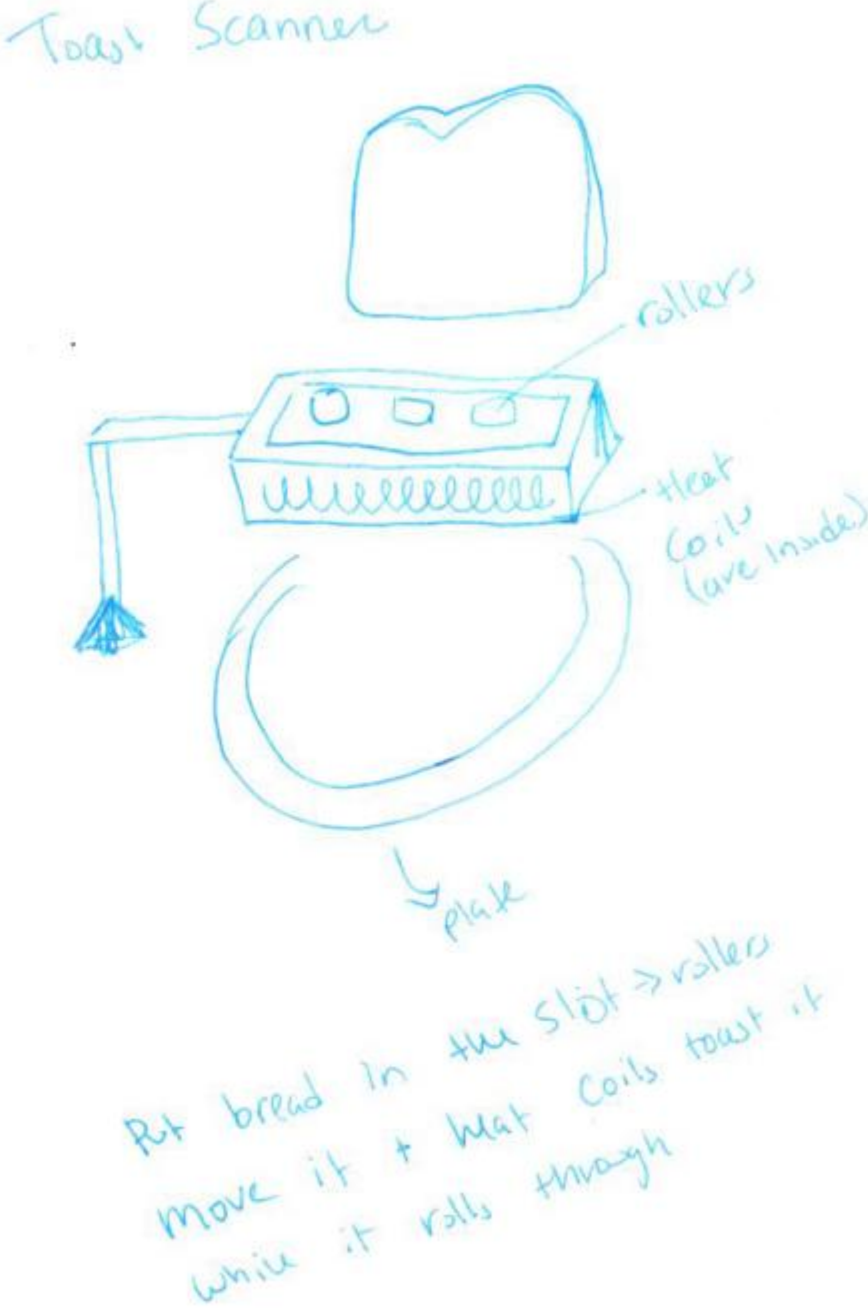


Figure G-1: Guidelines Group, Participant 1, Concept 1

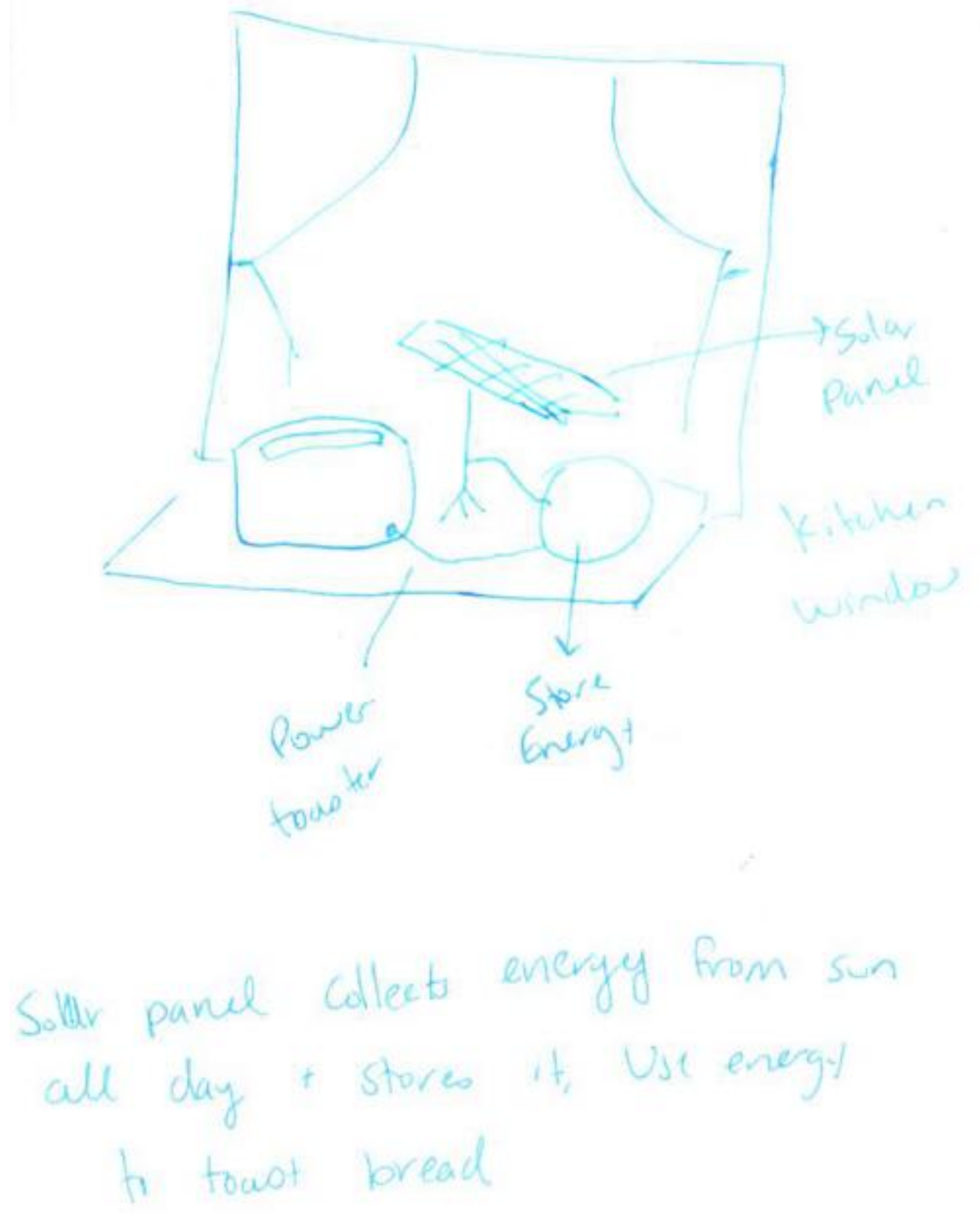


Figure G-2: Guidelines Group, Participant 1, Concept 2

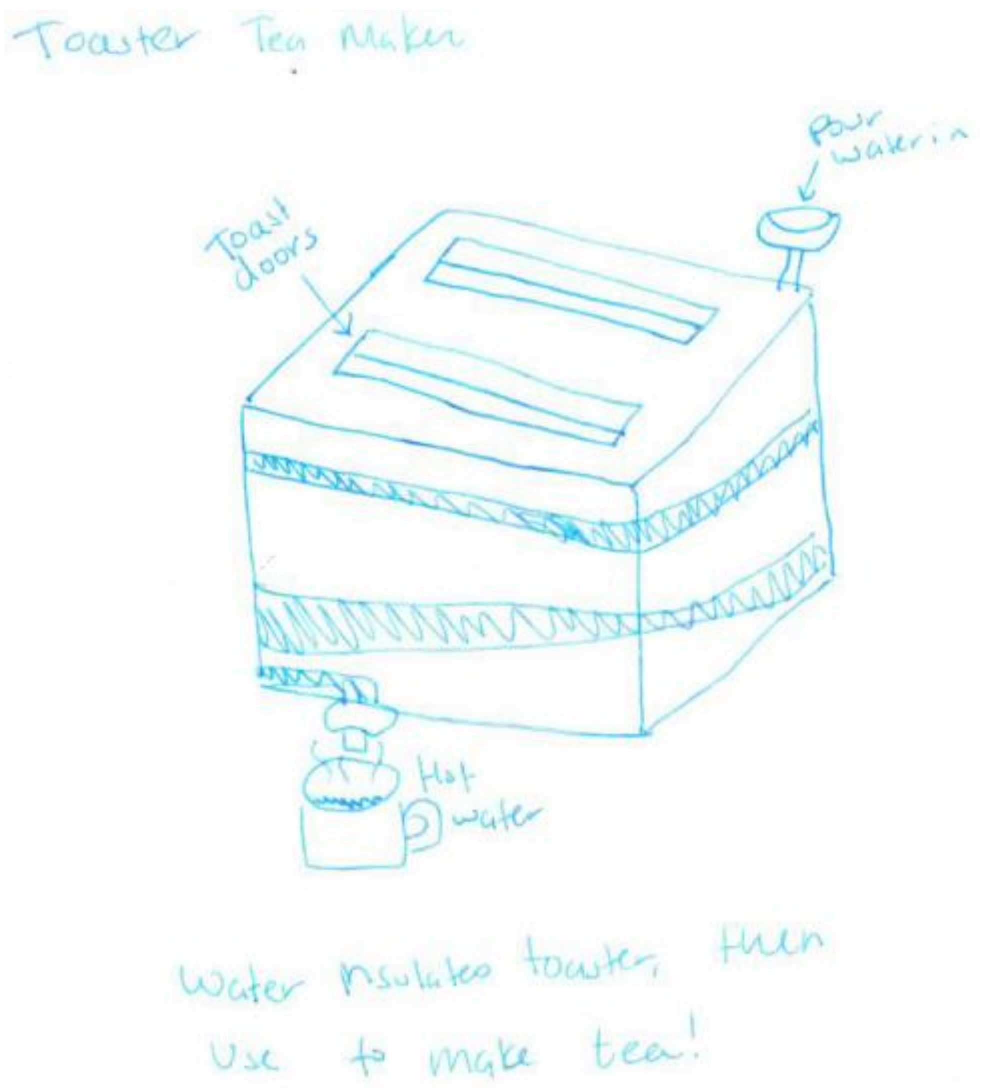


Figure G-3: Guidelines Group, Participant 1, Concept 3

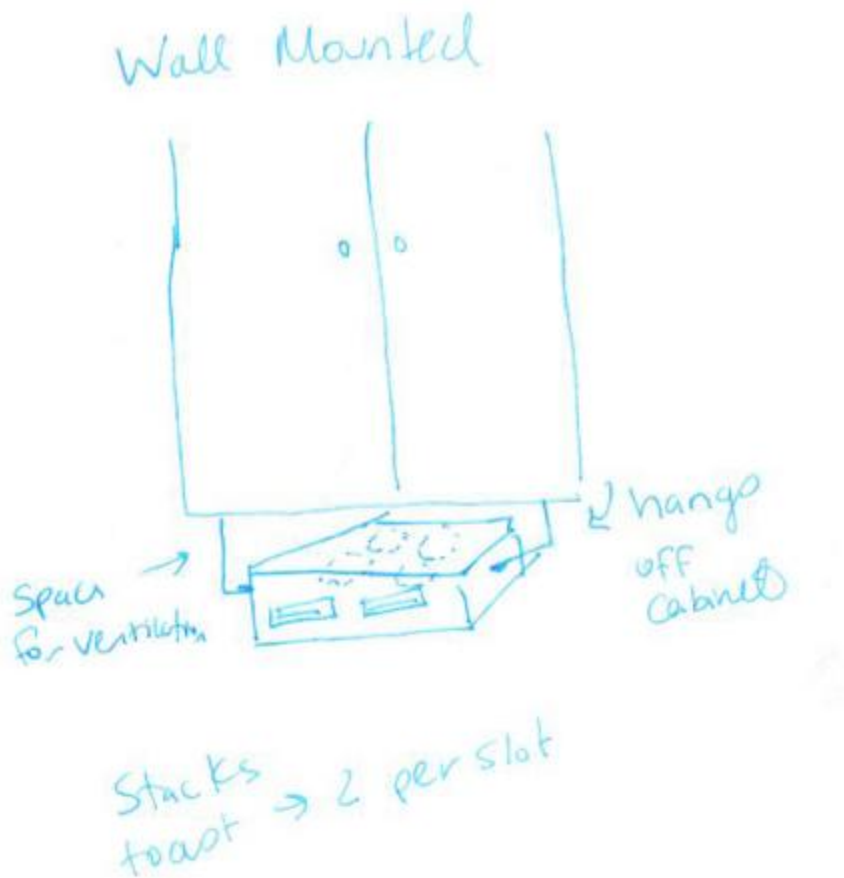


Figure G-4: Guidelines Group, Participant 1, Concept 4

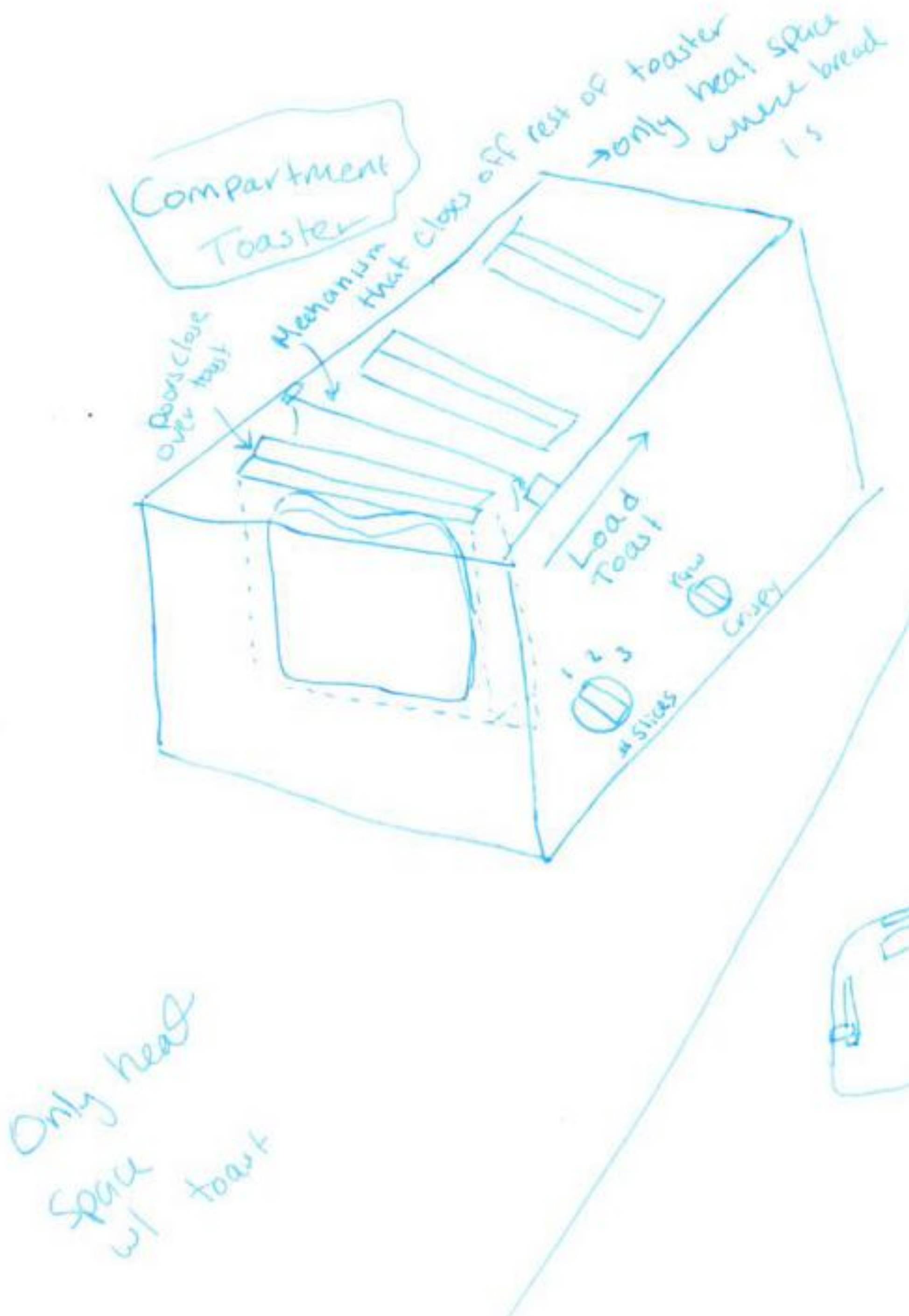


Figure G-5: Guidelines Group, Participant 1, Concept 5

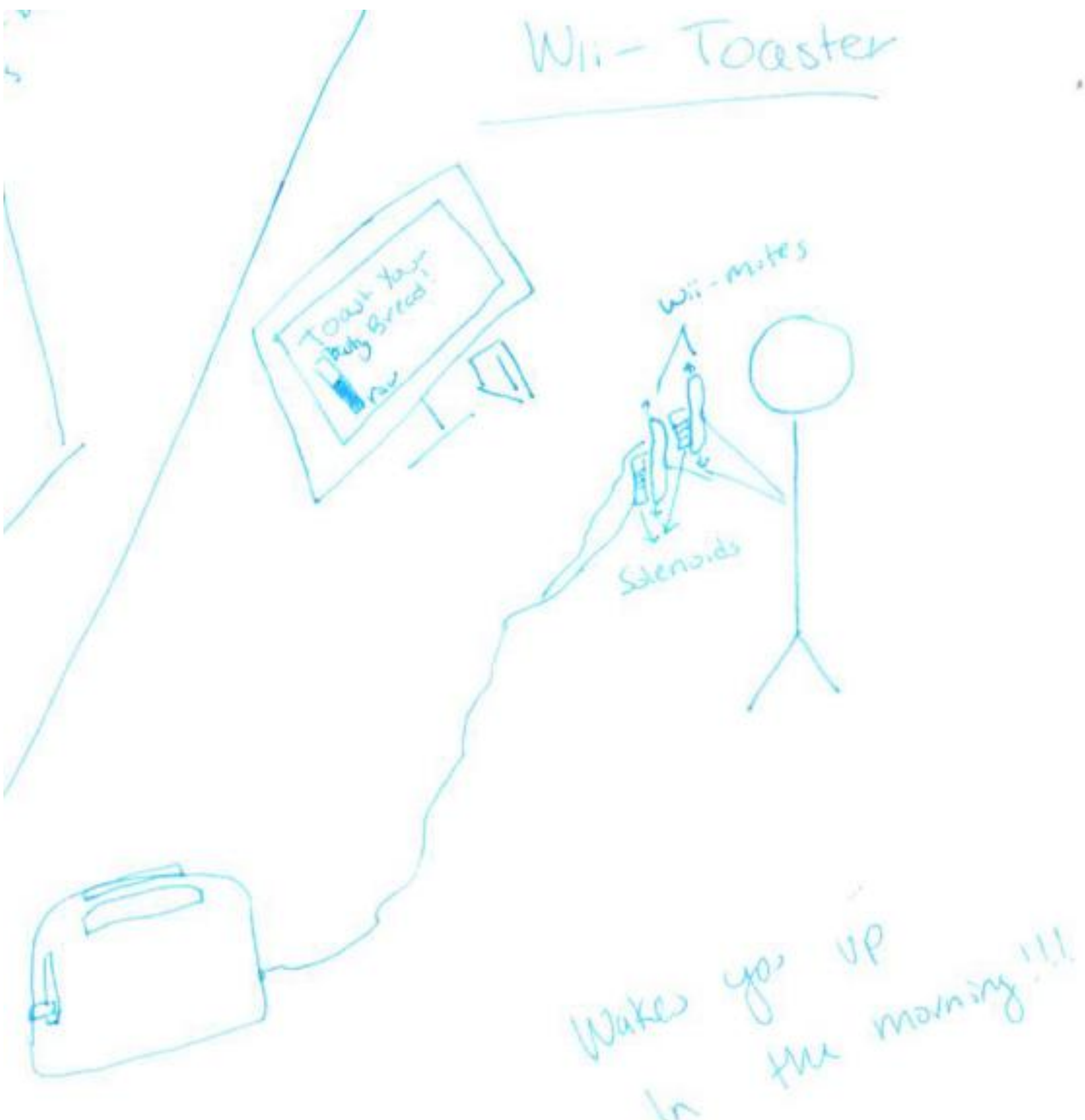


Figure G-6: Guidelines Group, Participant 1, Concept 6

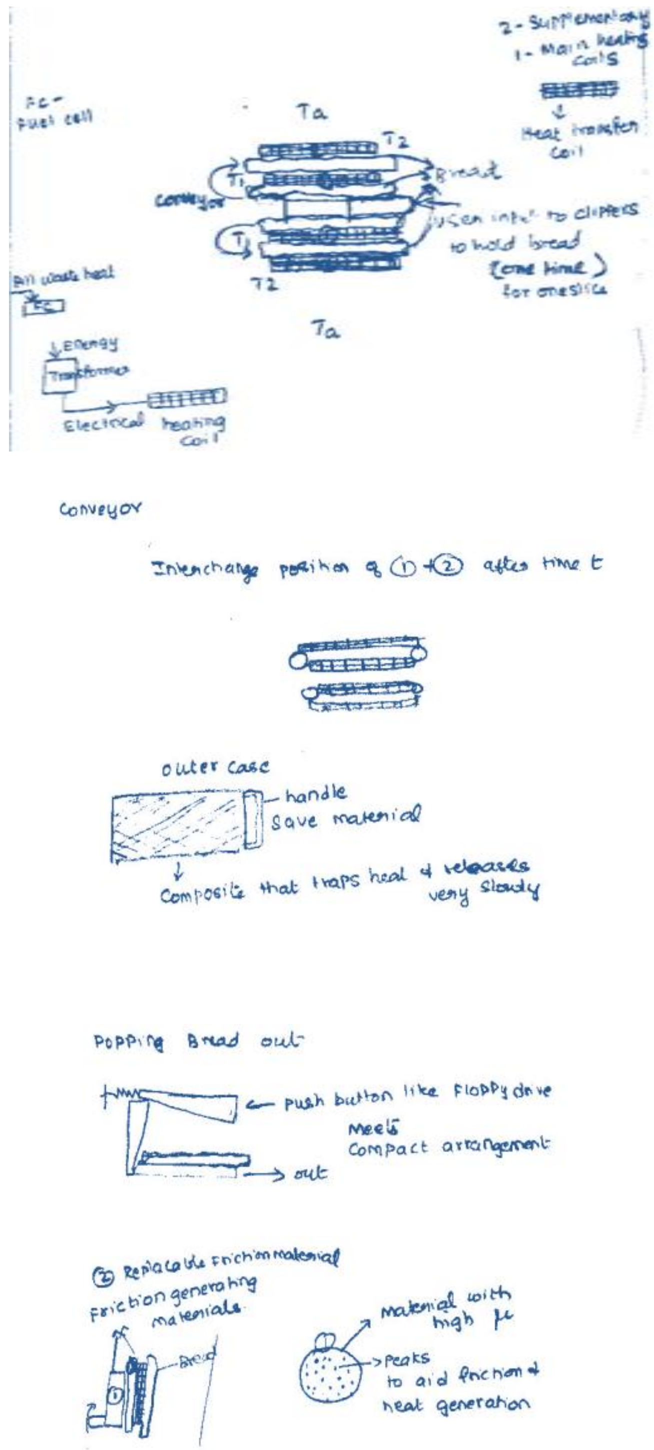


Figure G-7: Guidelines Group, Participant 2, Concept 1

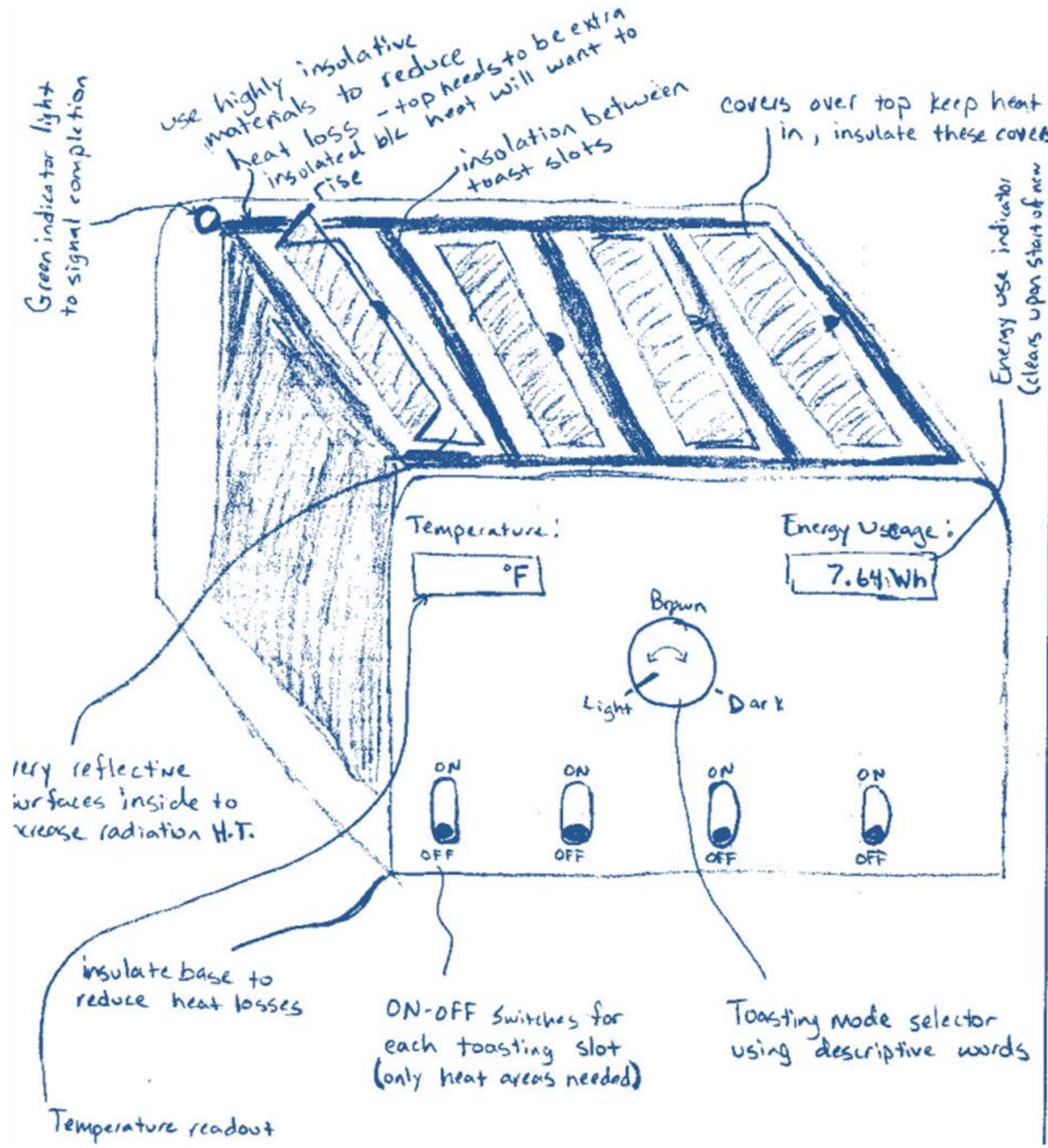


Figure G-8: Guidelines Group, Participant 3, Concept 1

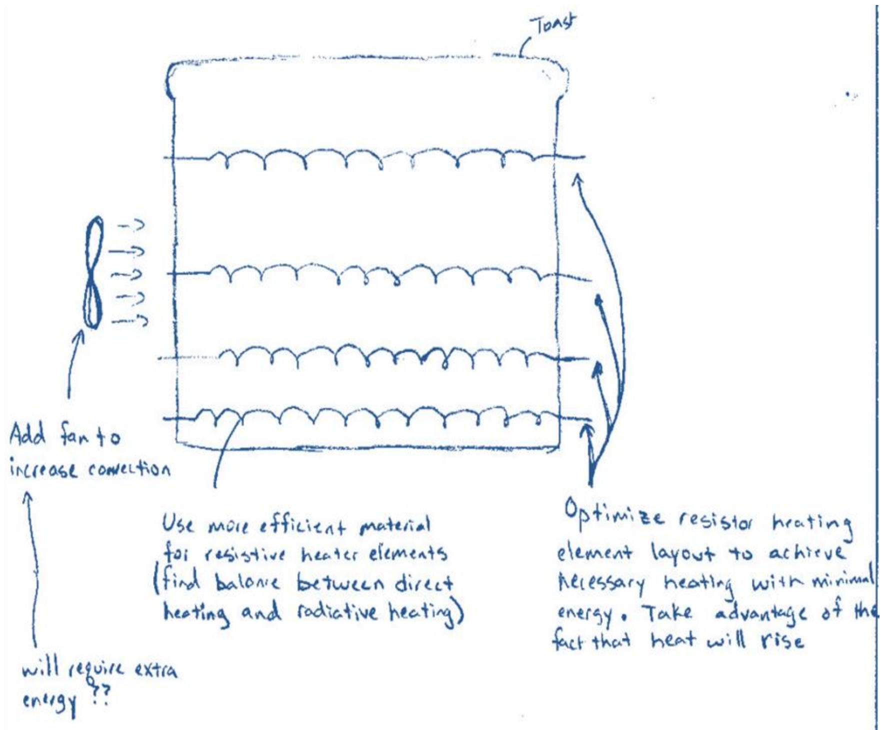


Figure G-9: Guidelines Group, Participant 3, Concept 1 - Continued

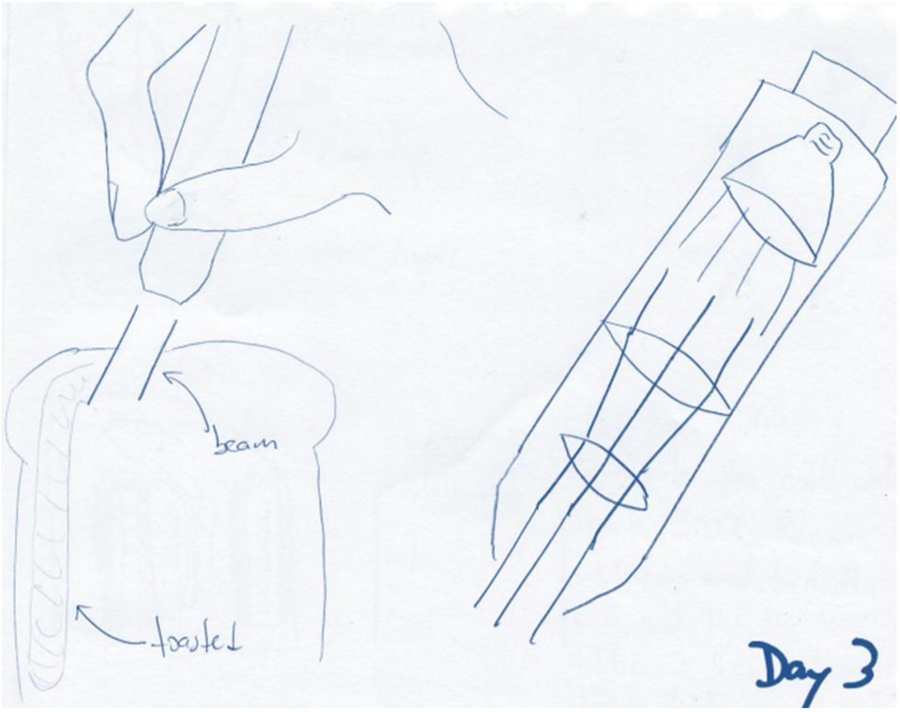


Figure G-10: Guidelines Group, Participant 4, Concept 1

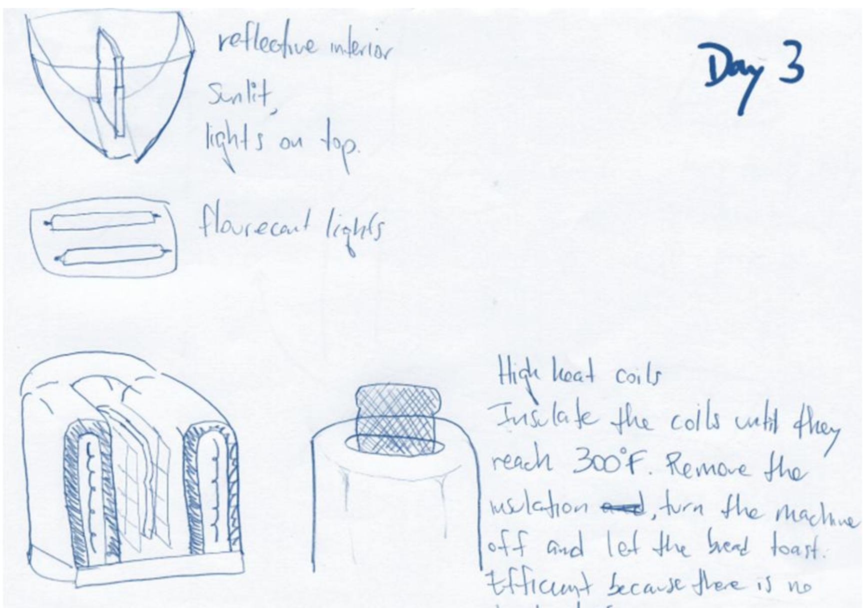


Figure G-11: Guidelines Group, Participant 4, Concept 2 and 3

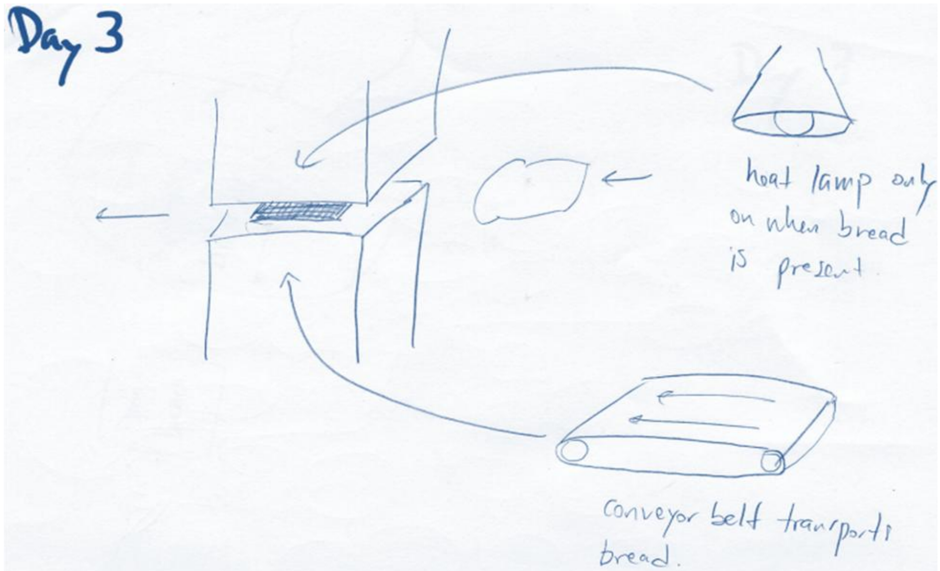


Figure G-12: Guidelines Group, Participant 4, Concept 4

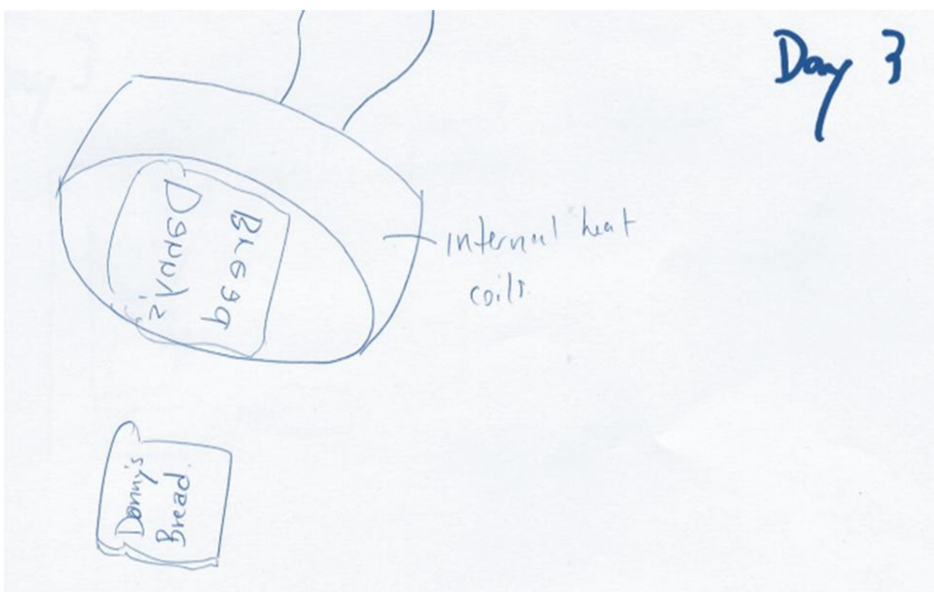


Figure G-13: Guidelines Group, Participant 4, Concept 5

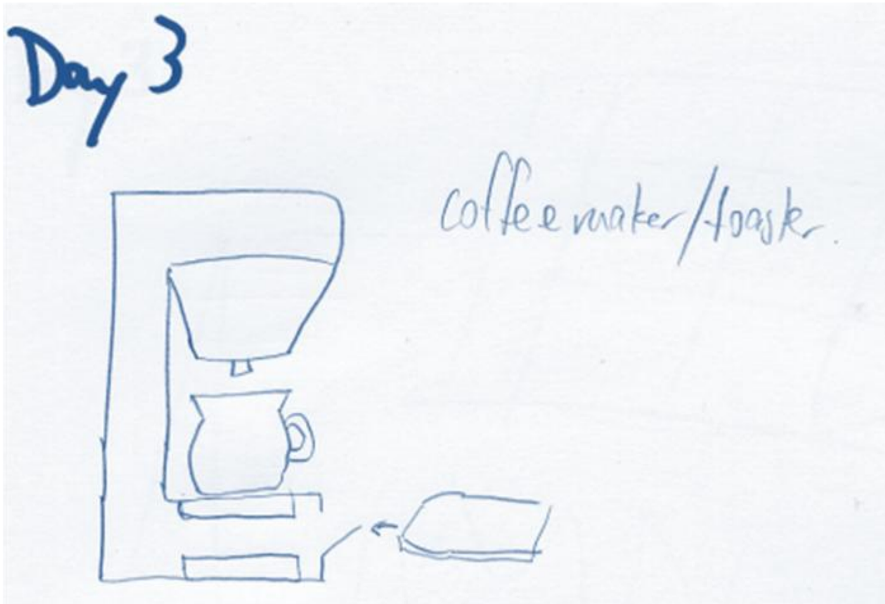


Figure G-14: Guidelines Group, Participant 4, Concept 6

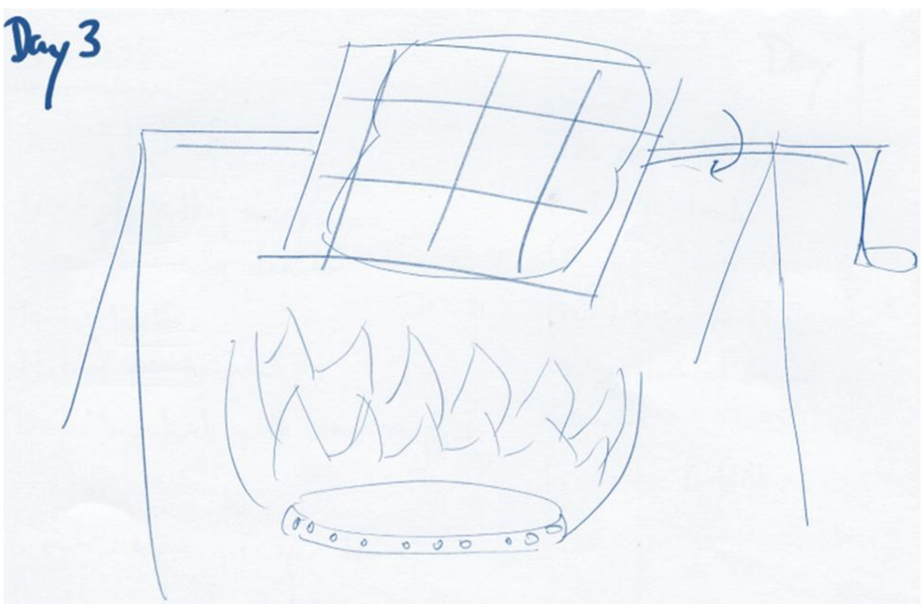


Figure G-15: Guidelines Group, Participant 4, Concept 7

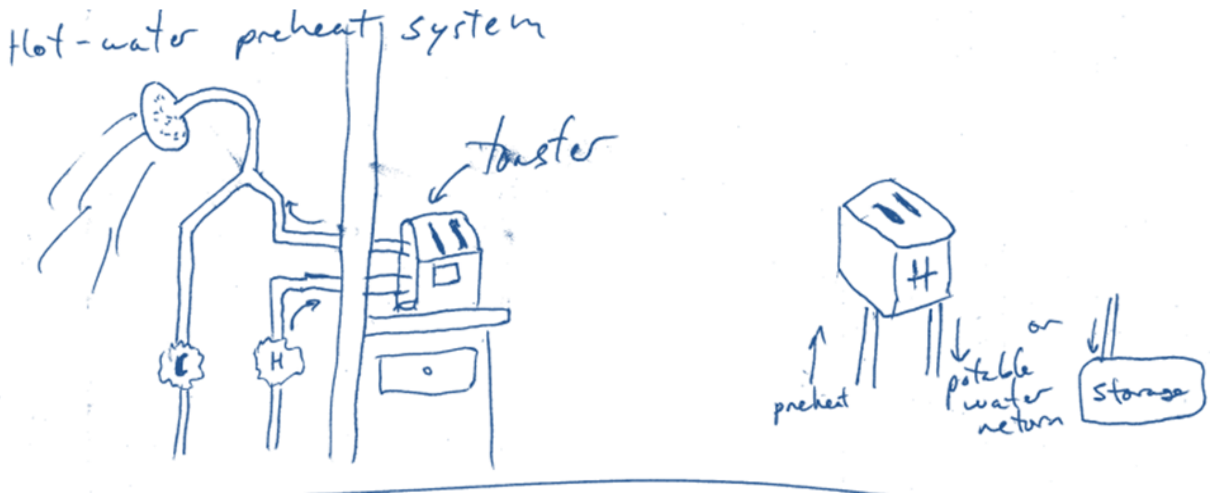


Figure G-16: Guidelines Group, Participant 5, Concept 1

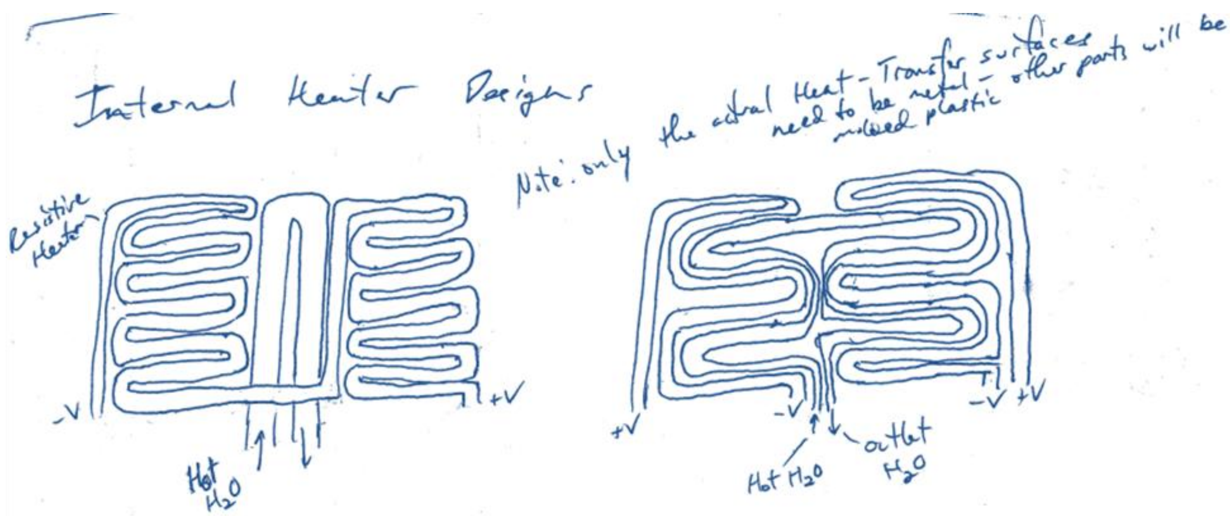


Figure G-17: Guidelines Group, Participant 5, Concept 2

Appendix H : Control Group's Generated Toaster Concepts

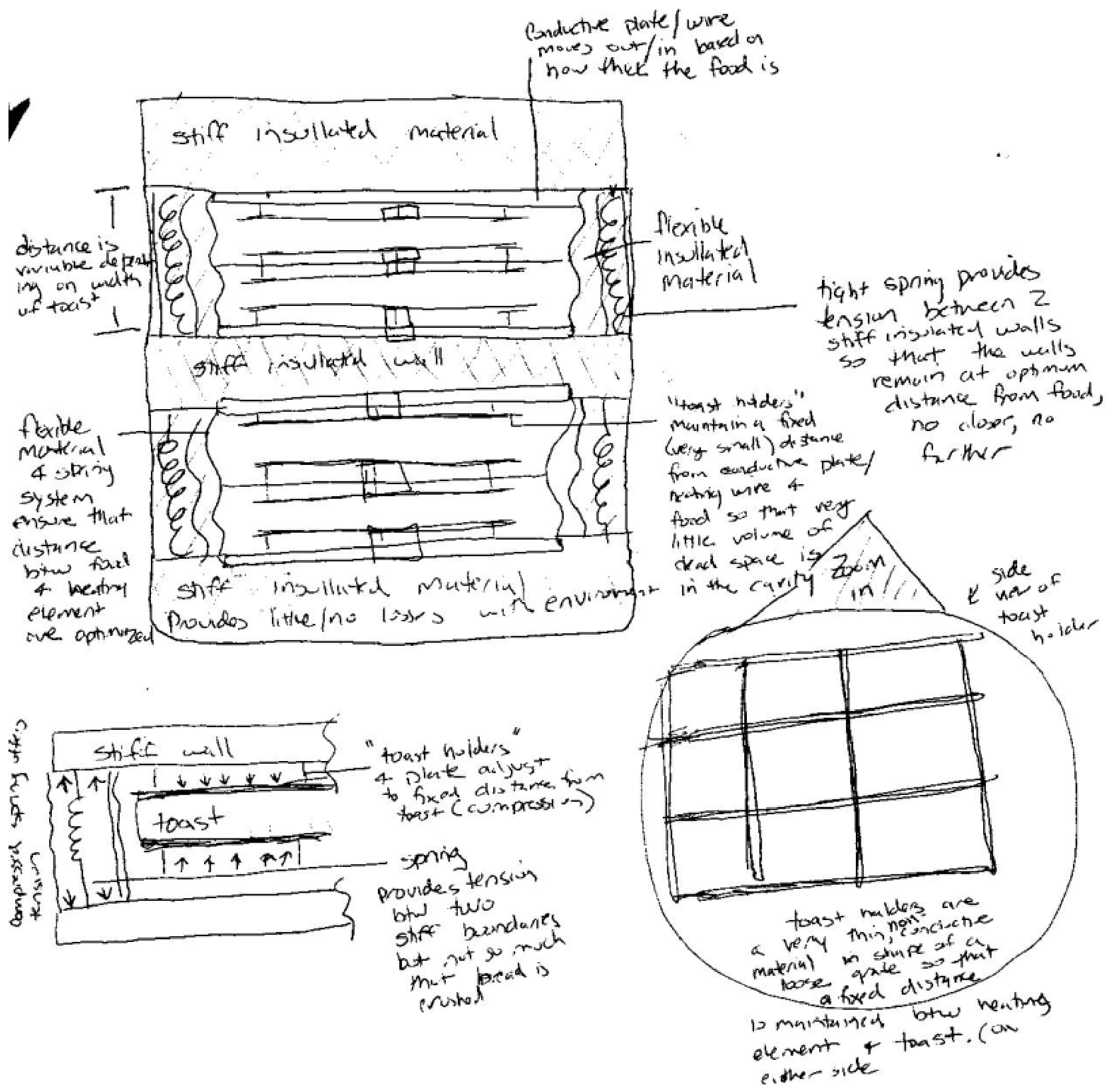


Figure H-1: Control Group, Participant 1, Concept 1

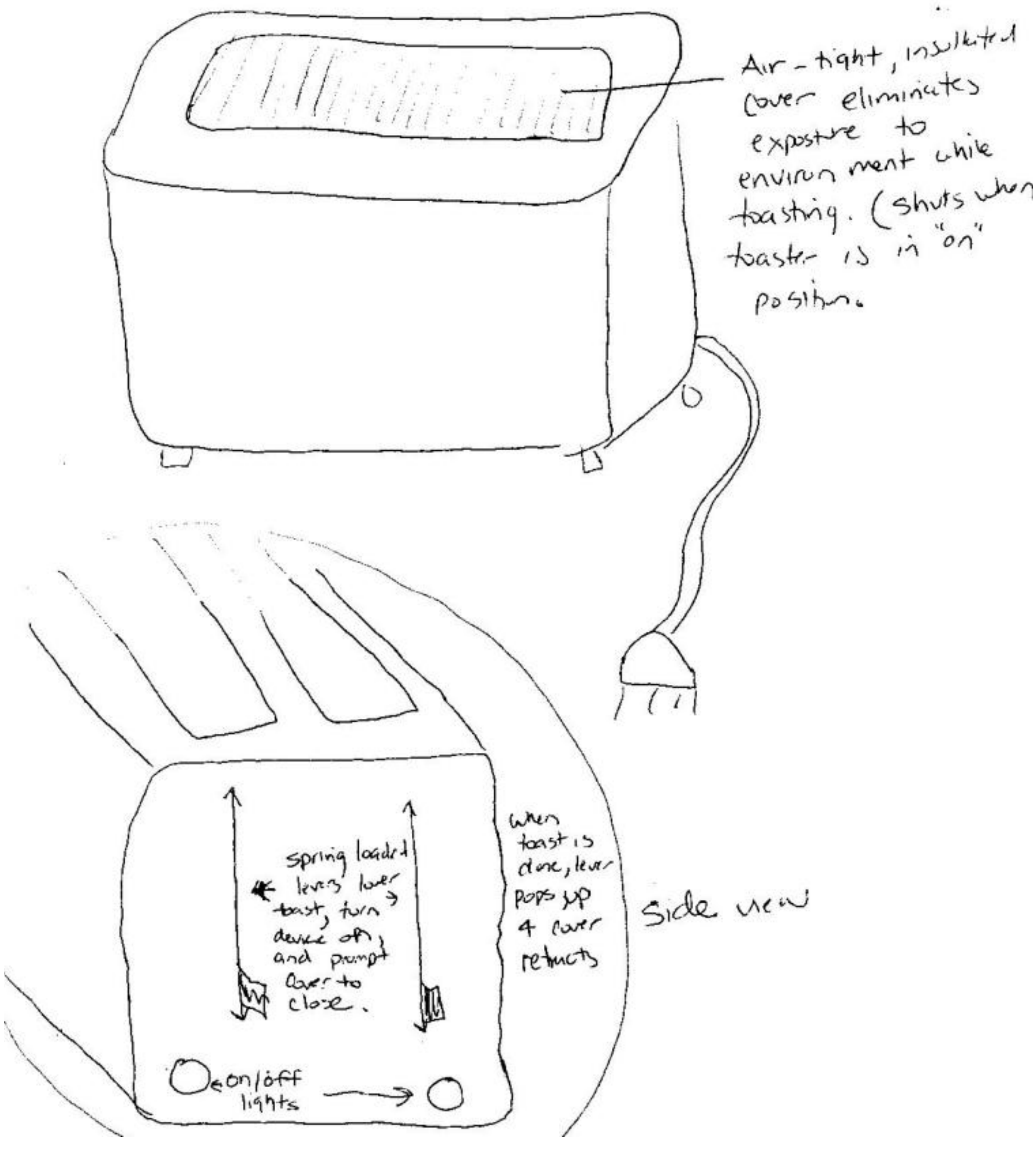


Figure H-2: Control Group, Participant 1, Concept 1 Continued

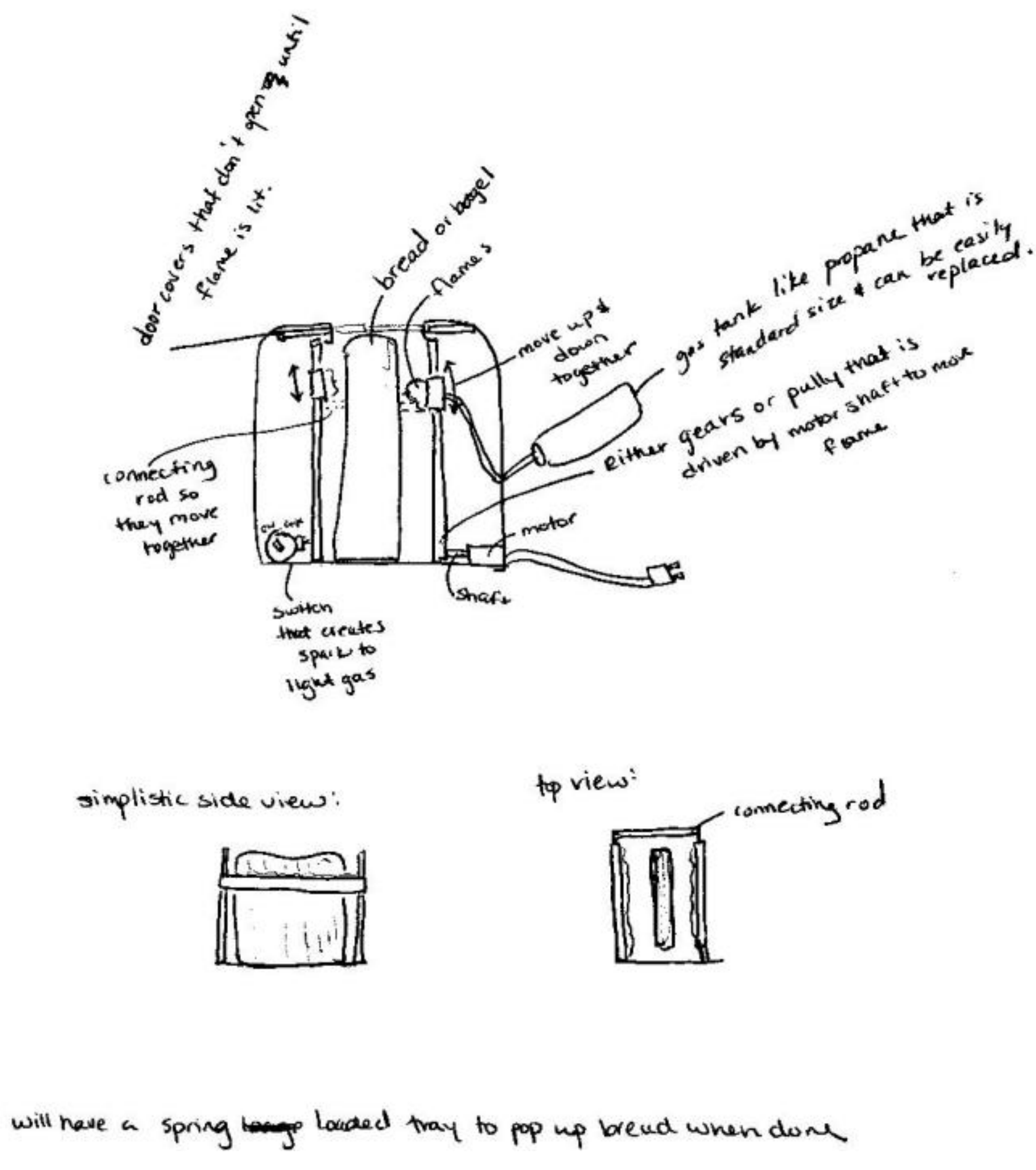


Figure H-3: Control Group, Participant 2, Concept 1

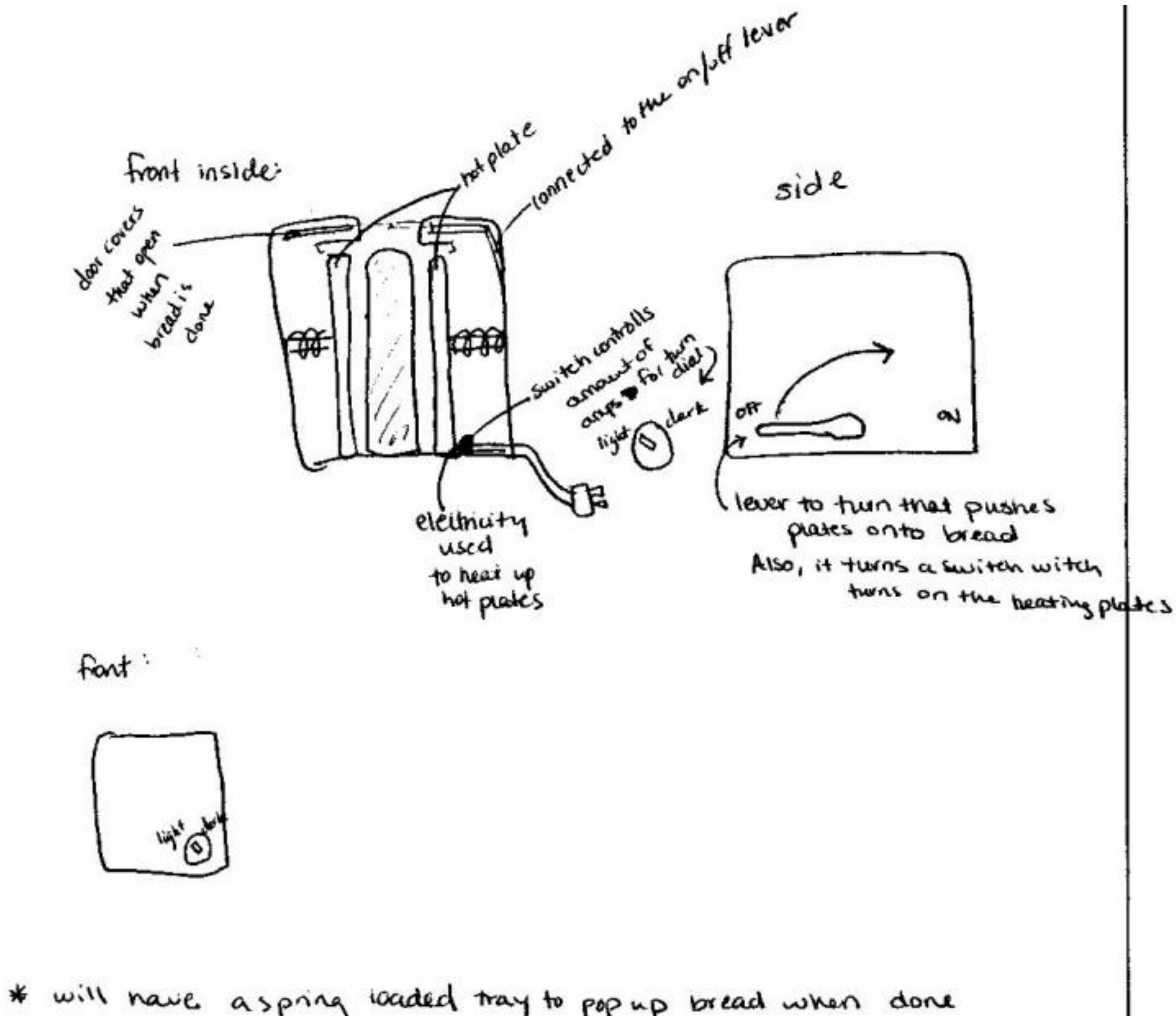


Figure H-4: Control Group, Participant 2, Concept 2

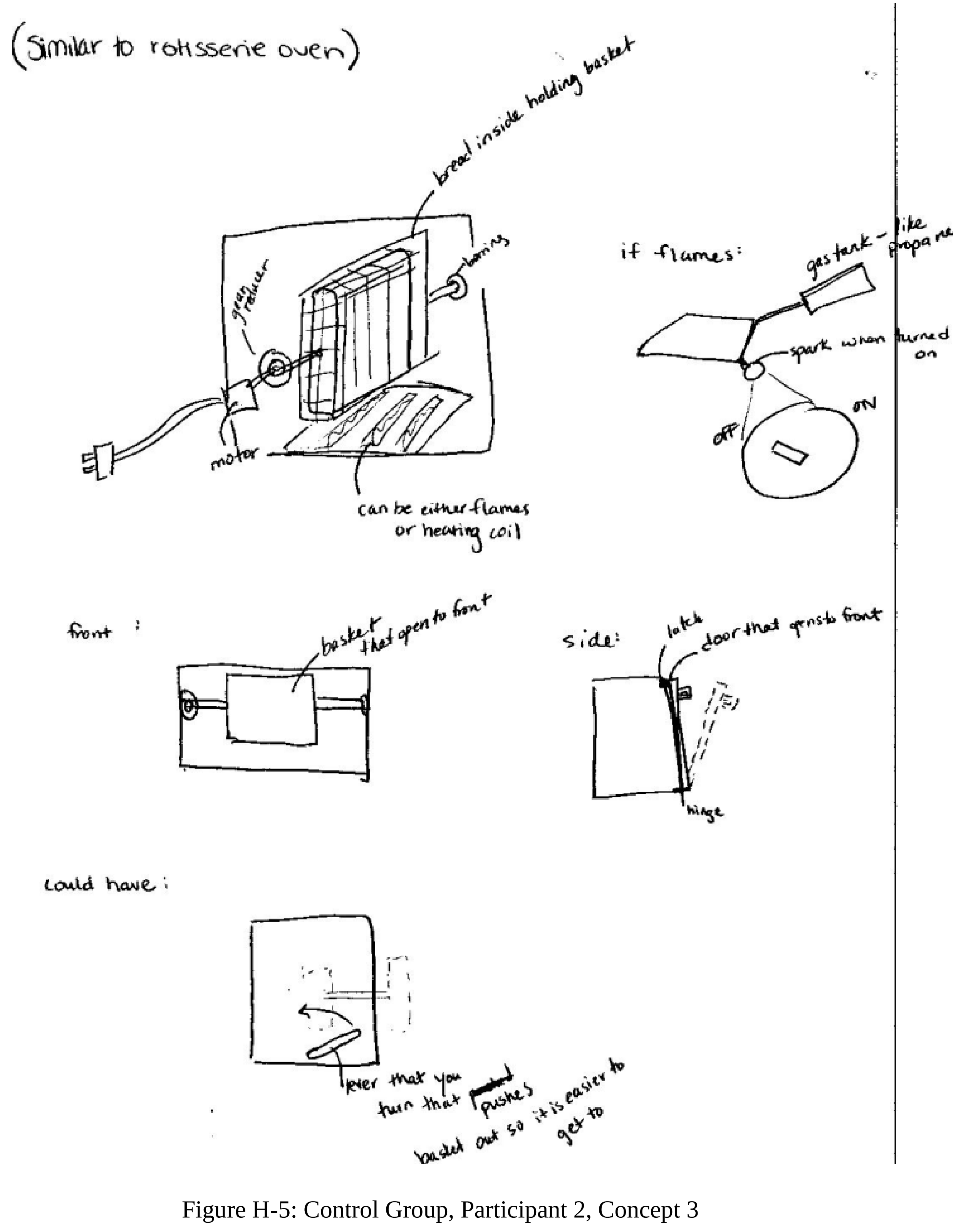


Figure H-5: Control Group, Participant 2, Concept 3

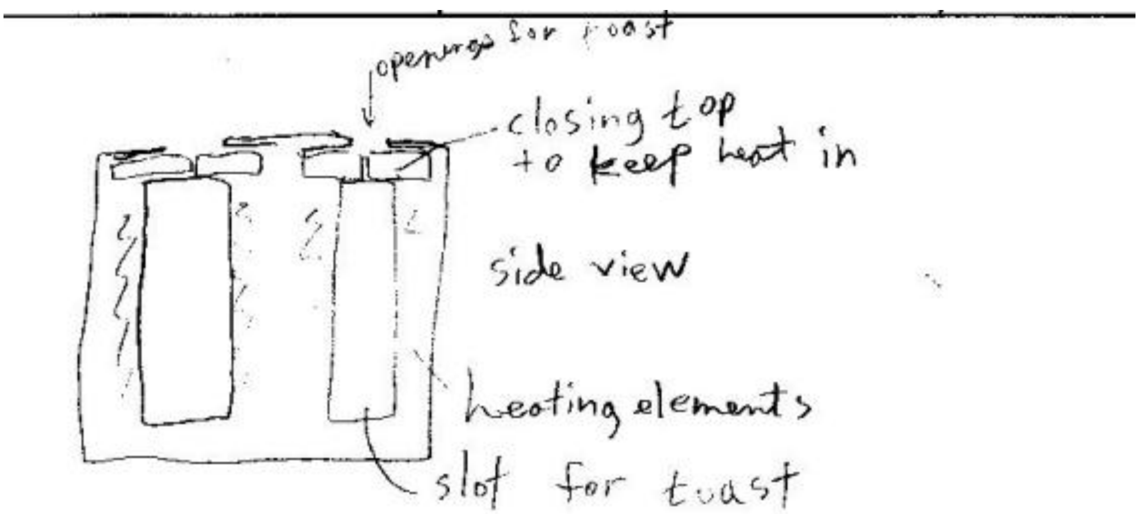


Figure H-6: Control Group, Participant 3, Concept 1

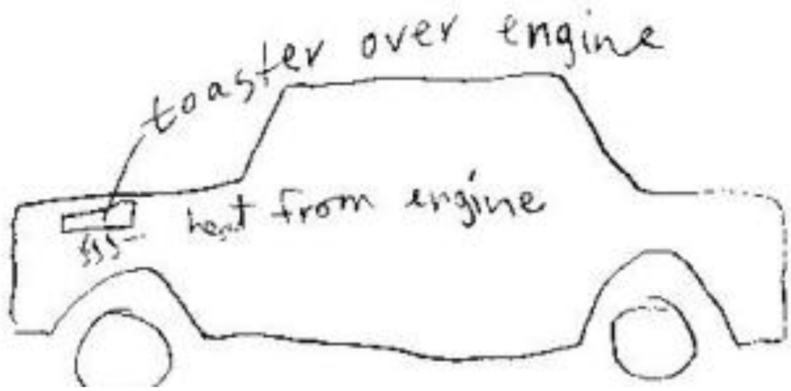


Figure H-7: Control Group, Participant 3, Concept 2

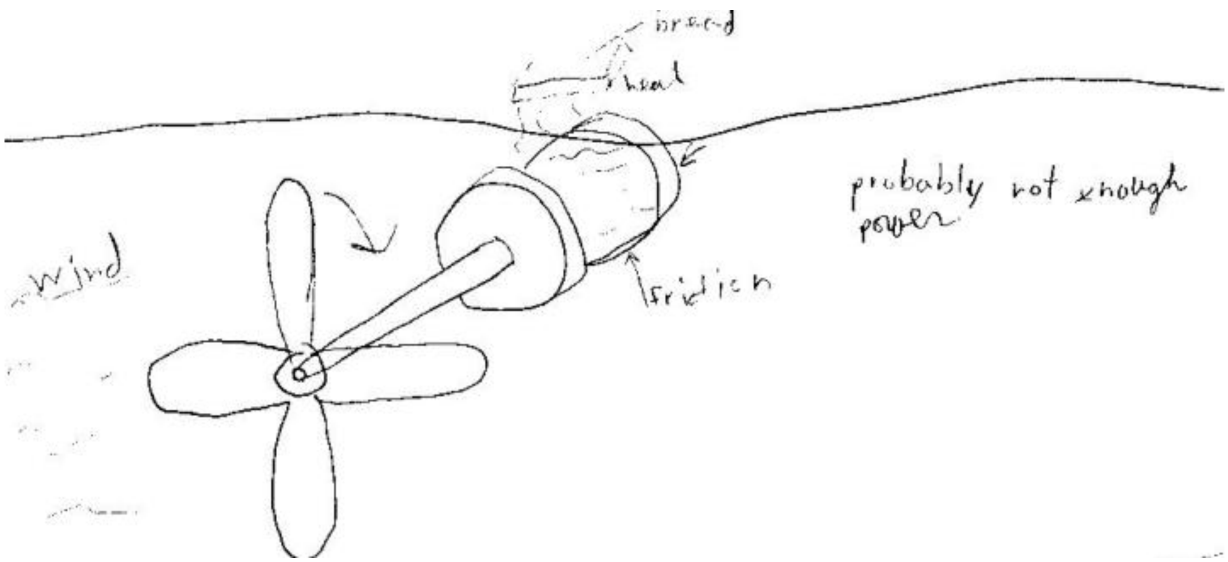


Figure H-8: Control Group, Participant 3, Concept 3

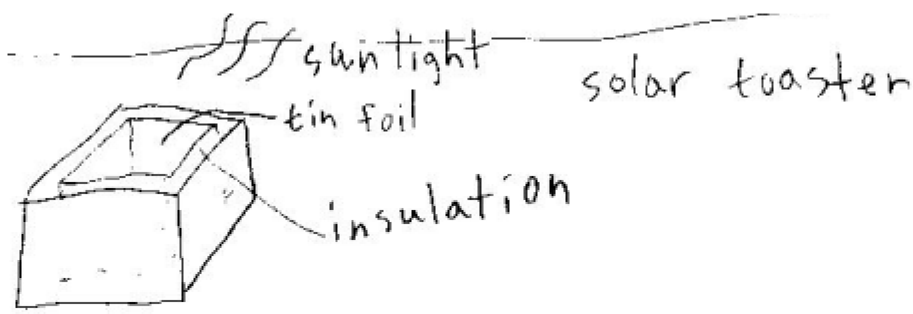


Figure H-9: Control Group, Participant 3, Concept 4

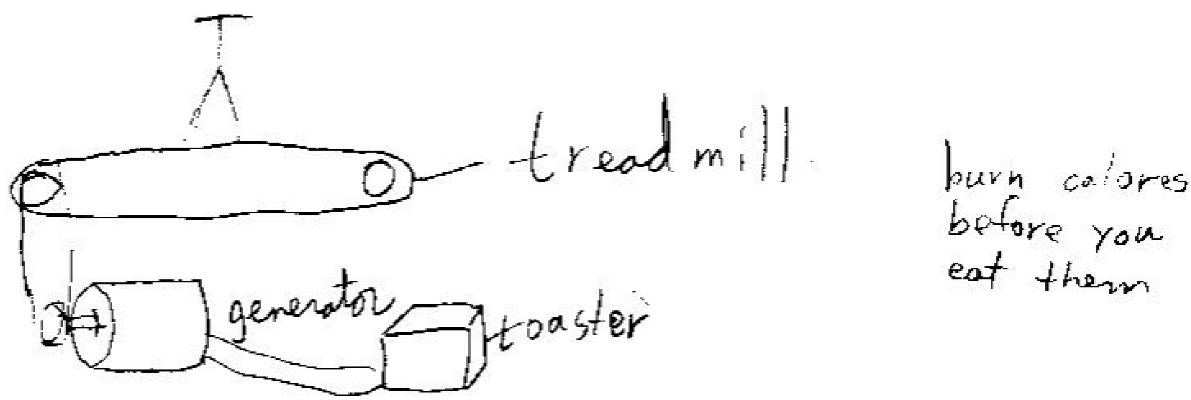


Figure H-10: Control Group, Participant 3, Concept 5

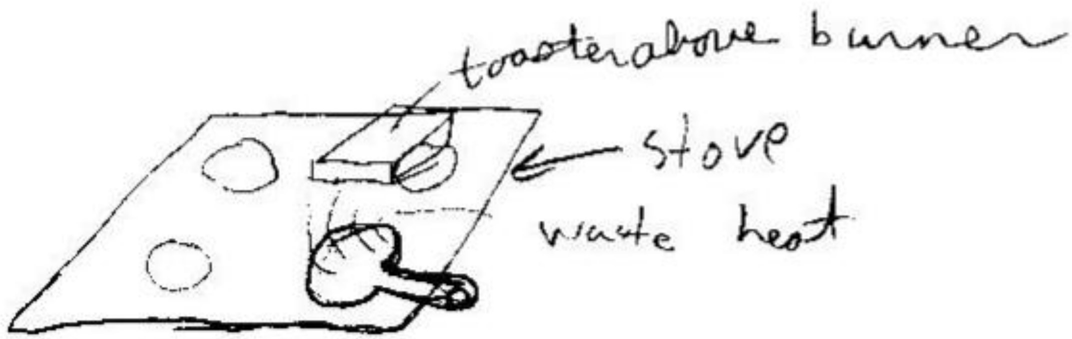


Figure H-11: Control Group, Participant 3, Concept 6

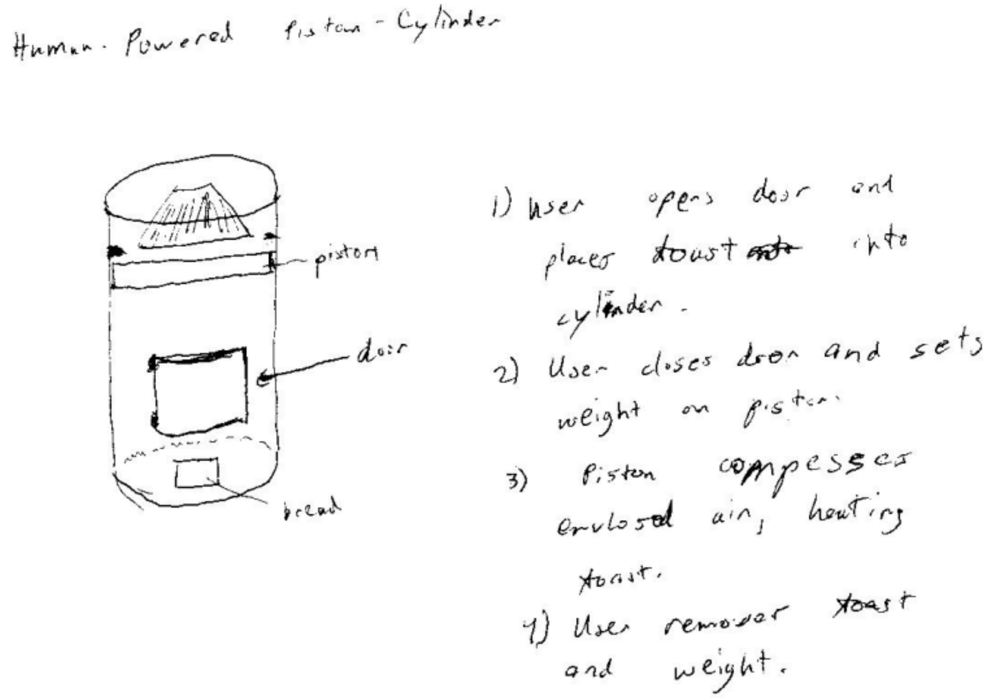


Figure H-12: Control Group, Participant 4, Concept 1

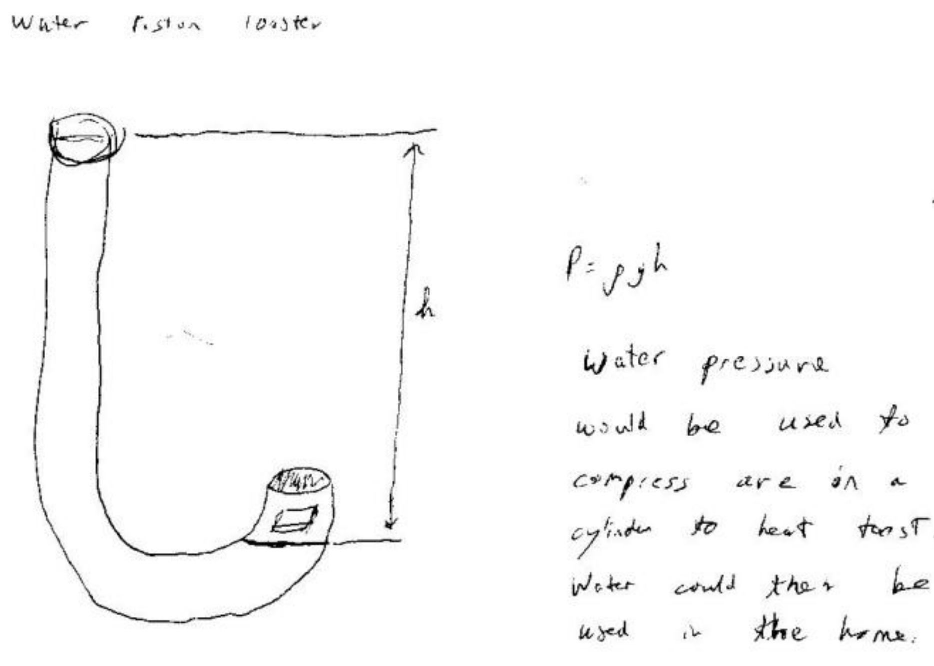


Figure H-13: Control Group, Participant 4, Concept 2

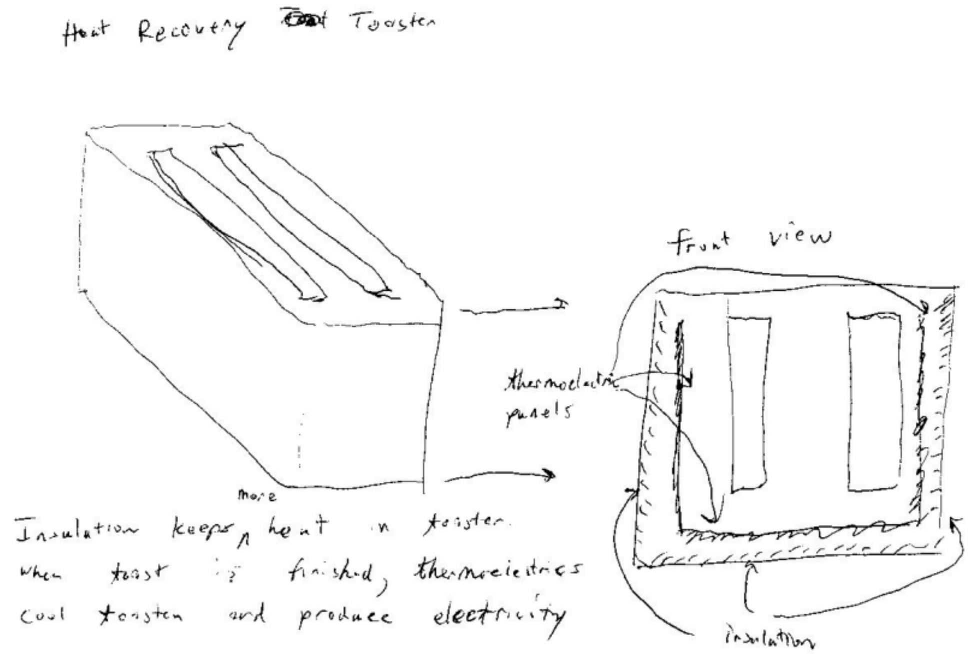


Figure H-14: Control Group, Participant 4, Concept 3

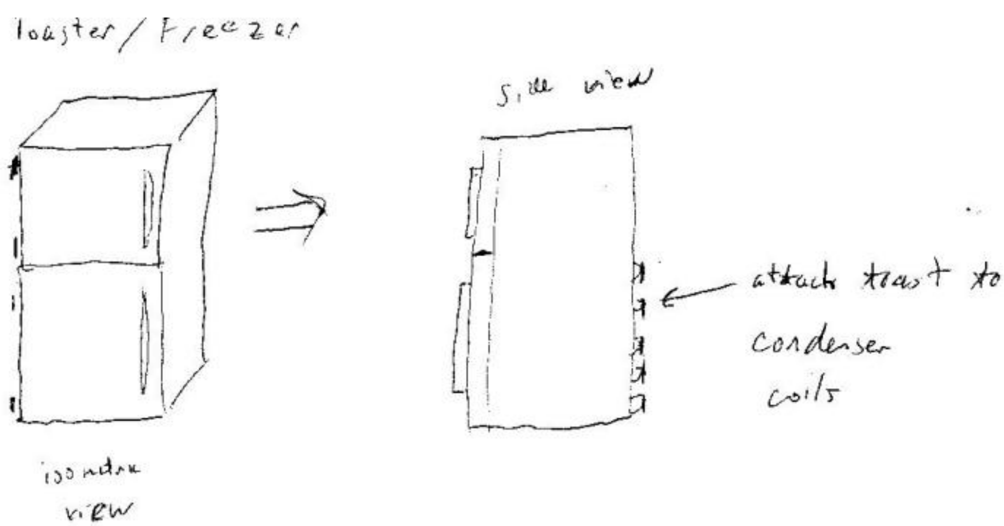


Figure H-15: Control Group, Participant 4, Concept 4

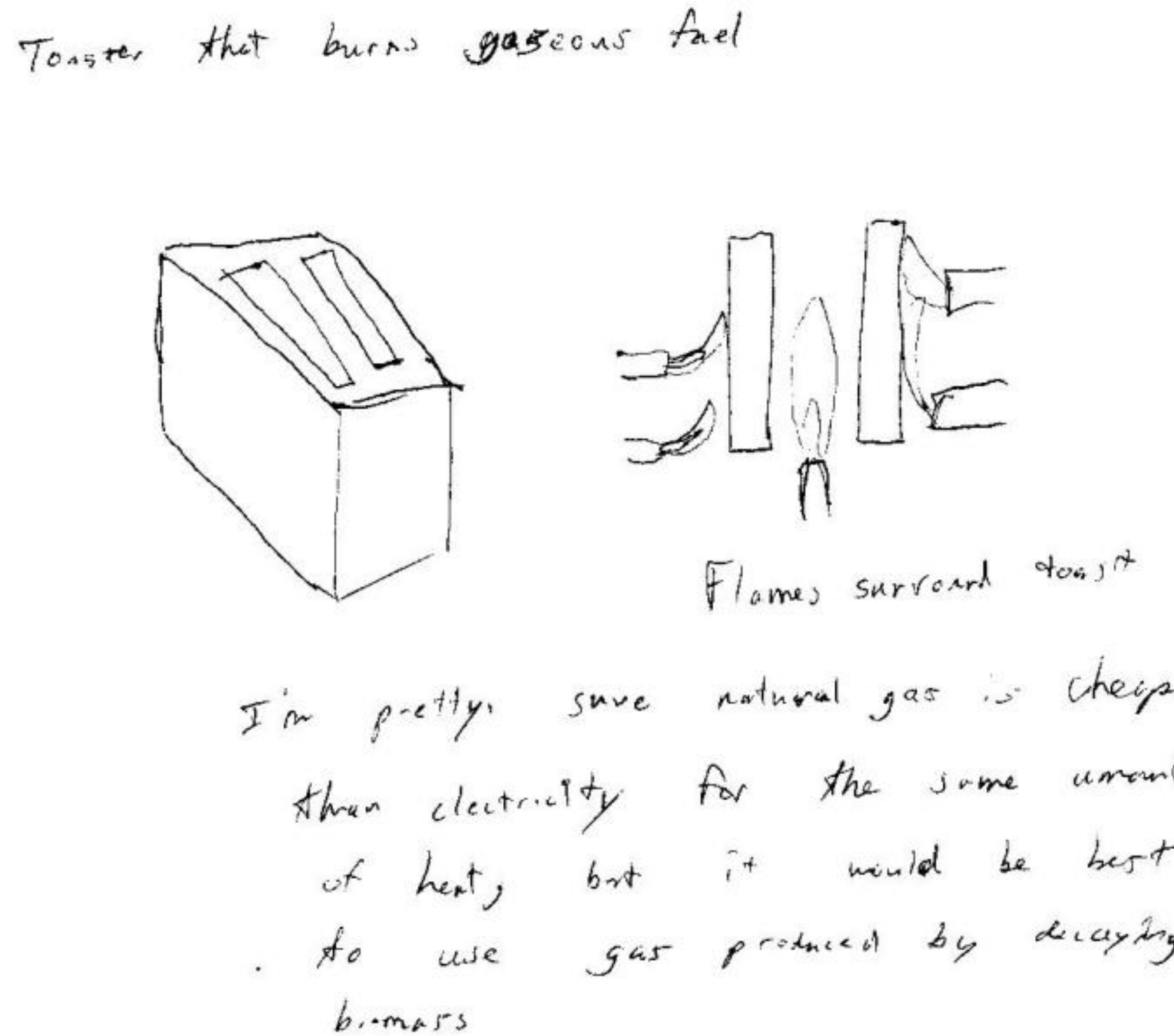


Figure H-16: Control Group, Participant 4, Concept 5

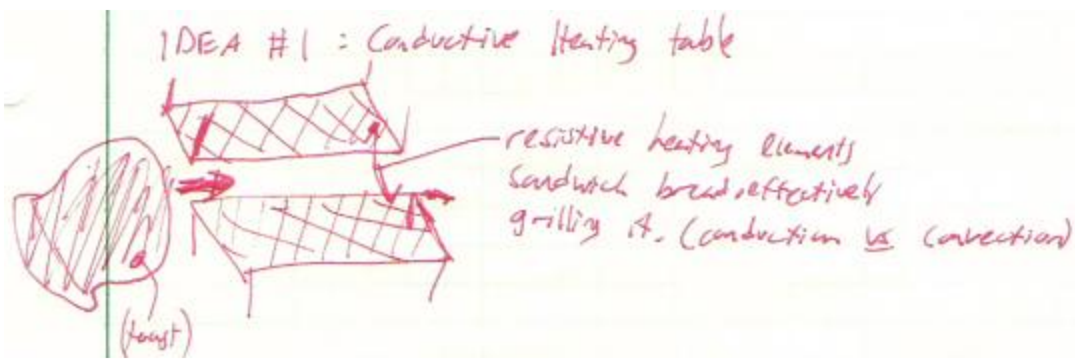


Figure H-17: Control Group, Participant 5, Concept 1

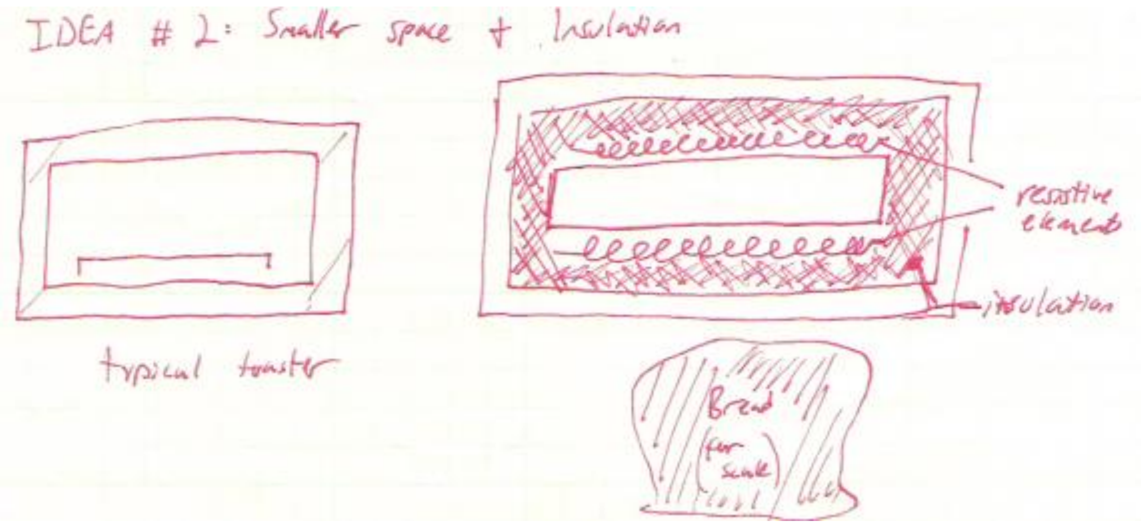


Figure H-18: Control Group, Participant 5, Concept 2

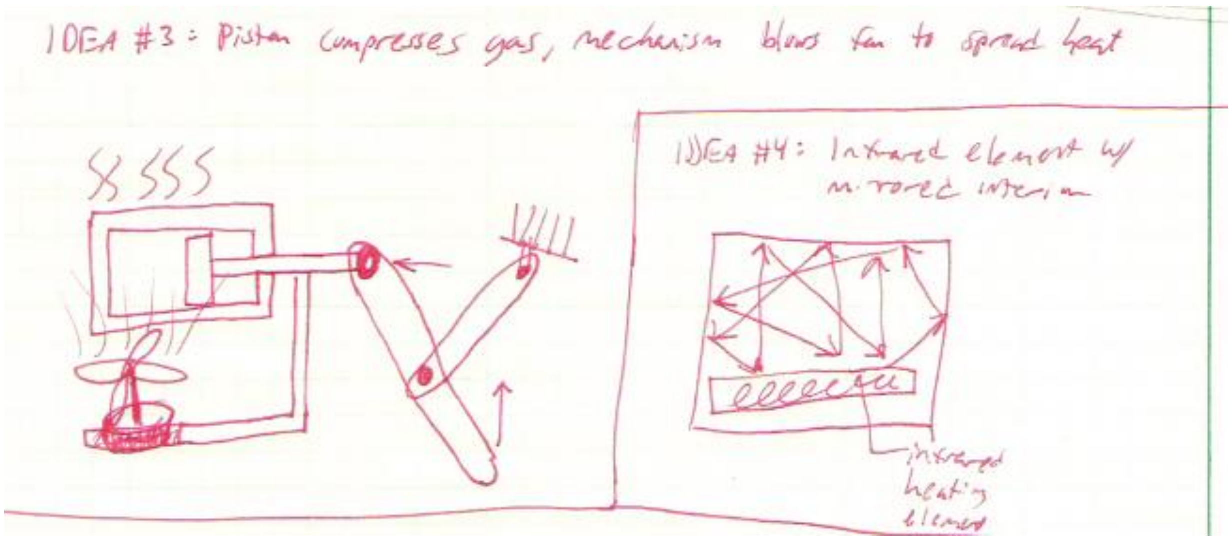


Figure H-19: Control Group, Participant 5, Concepts 3 and 4

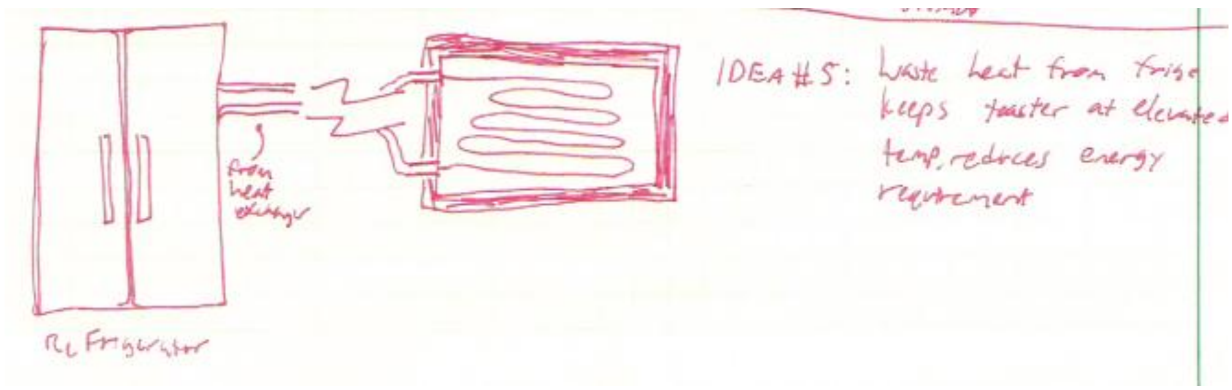


Figure H-20: Control Group, Participant 5, Concept 5

Appendix I : Analysis of Concepts

This appendix lists each feature assessed from the toaster concept generation studies, as explained in Chapter 5. It serves as supplementary information and sample calculations for the interested reader. Each feature is outlined by the function it serves. Boxes above the illustration show which groups and quality criterion the feature passed. Underneath the sketch of the feature, decision for or against viability and practicality are explained. Then, a table of guidelines presents the guidelines that the feature violates or follows. Finally, the table of guidelines is followed by an assessment of the environmental tradeoffs due to the feature.

A. IMPORT HUMAN ON/SETTING

A.1 Combine slot controls

Guidelines Group	Practical and Viable	Greener

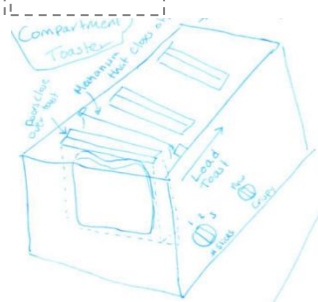


Figure I-1: Sketch of Combine Slot Controls

Viable: YES
Explanation: Each switch in a circuit or separate circuits allows power to flow to the correct bread slots.
Practical: YES
Explanation: Does not violate any of the customer needs or incur excessive costs. It integrates with daily, kitchen routine of an average residence.

Table I-1: Guidelines Corresponding to Combined Slot Controls

Followed Guidelines	**Violated Guidelines**
1. Implementing default power down for subsystems that are not in use 2. Incorporating part-load operation and permit users to turn off systems in part or whole 3. Minimizing the volume and weight of parts and materials to which energy is transferred 4. Incorporating intuitive controls for resource-saving features *5. Incorporating automatic or manual tuning capabilities.*	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: A small, two slot toaster heats both slots every use. During uses where only one slice of toast is being heated, a dial would save about half of the energy. It is probable that only one slice of toast will be heated often enough to outweigh the addition of a switch or dial.

A.2 Separate Slot Controls

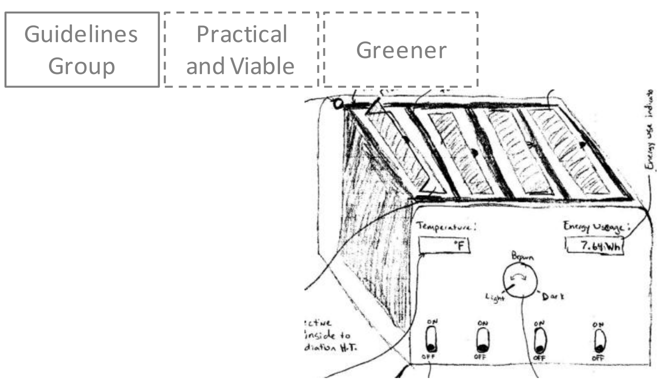


Figure I-2: Sketch of Separate Slot Controls

Viable: YES
Explanation: Each switch in a circuit or separate circuits allows power to flow to the correct bread slots.
Practical: YES
Explanation: Does not violate any of the customer needs or incur excessive costs. It integrates with daily, kitchen routine of an average residence.

Table I-2: Guidelines Corresponding to Separate Slot Controls

Followed Guidelines	Violated Guidelines
1. Implementing default power down for subsystems that are not in use	1. Minimizing the number of components
2. Incorporating part-load operation and permit users to turn off systems in part or whole	
3. Minimizing the volume and weight of parts and materials to which energy is transferred	
4. Incorporating intuitive controls for resource-saving features	
5. Incorporating automatic or manual tuning capabilities.	
6. Creating separate modules for tasks with conflicting requirements or solutions	

Significant Tradeoff Does Not Exist: A small, two slot toaster heats both slots every use. During uses where only one slice of toast is being heated, a dial would save about half of the energy. It is probable that only one slice of toast will be heated often enough to outweigh the addition of a switch or dial. Separately controlled slots could also increase the life of a product, as some slots on a multi-slot toaster might break before others.

A.3 Dial Darkness/Crispiness

Guidelines Group	Control Group	Practical and Viable	Greener

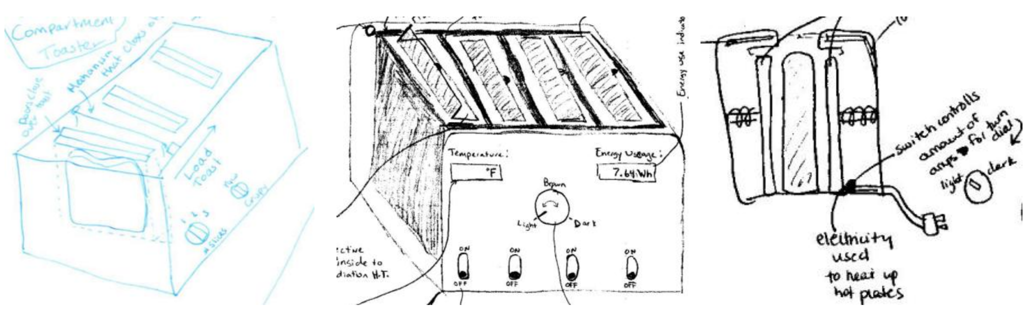


Figure I-3: Sketches of Dial Darkness/Crispiness

Viable: YES

Explanation: This function is on a typical benchmark toaster.
Practical: YES
Explanation: This function is on a typical benchmark toaster.

Table I-3: No Guidelines Correspond to Dial Darkness/Crispiness

Followed Guidelines	Violated Guidelines
No Change in Guidelines	No Change in Guidelines

B. Actuate Energy

B.1 Sense Moisture

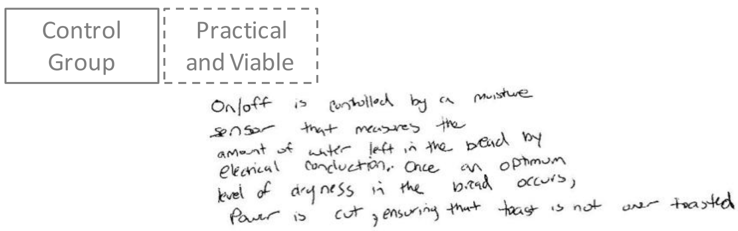


Figure I-4: Description of Sense Moisture

Viable: YES
Explanation: Dryers exist with moisture sensors. These sensors reduce dryer run time based upon their readings.
Practical: YES
Explanation: Does not violate any of the customer needs and it integrates with daily, kitchen routine of an average residence. Cost could be managed in mass production if the sensor is only needed in one slot. Cheapest moisture sensor and toaster prices are $30 and $10 respectively.

Table I-4: Guidelines Corresponding to Sense Moisture

Followed Guidelines	Violated Guidelines
1. *Minimizing the quantity of resource use by optimizing its rate and duration* 2. *Incorporating automatic or manual tuning capabilities.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: A darkness setting already exists that would be as well calibrated to user set preference as a moisture sensor. The moisture sensor provides advantage for very thin, quick toasting bread and very thick, slow toasting bread. It can be assumed that a user will learn at what setting to toast their bread to choose the correctly timed darkness setting. Addition of components for a moisture sensor will ultimately increase the impact of component manufacture while not reducing energy use.

B.2 Sense Bread's Presence

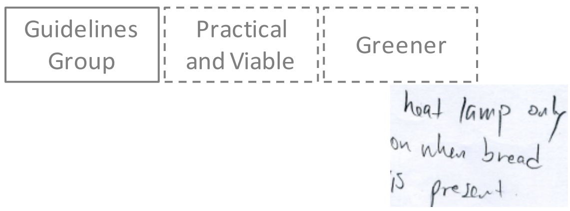


Figure I-5: Description of Sense Bread's Presence

Viable: YES
Explanation: Sensing the bread presence could be achieved through mechanical or electrical mechanisms. An example would be a switch triggered by the bread's weight.
Practical: YES
Explanation: Does not violate any of the customer needs or incur excessive costs. It integrates with daily, kitchen routine of an average residence.

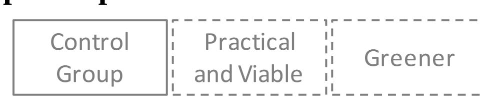
Table I-5: Guidelines Corresponding to Sense Bread's Presence

Followed Guidelines	Violated Guidelines
1. Implementing default power down for subsystems that are not in use *2. Incorporating automatic or manual tuning capabilities.*	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: A small, two slot toaster heats both slots every use. During uses where only one slice of toast is being heated or instances where a toaster is turned on without any contents, a sensor would prevent waste of energy. A sensor could be a very simple switch with little impact.

C. MEASURE SOLID

C.4 Expand Space and insulation with bread



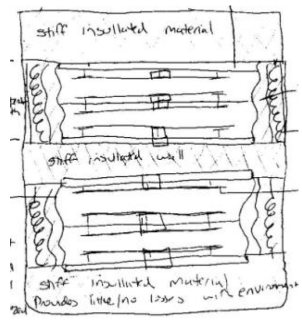


Figure I-6: Sketch of Expand Space and Insulation with Bread

Viable: YES
Explanation: The exact embodiment for this feature may possibly crush the bread with the springs. The sizing could be set manually with inserts or with a screw. Careful design would be required of enlarging sides (possibly telescoping walls. Expanding the insulation may not be possible as a candidate, expanding material could not be discovered.
Practical: YES
Explanation: Does not violate any of the customer needs or incur excessive costs. It integrates with daily, kitchen routine of an average residence.

Table I-6: Guidelines Corresponding to Expand Space and Insulation with Bread

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	1. Minimizing the number of components
2. Minimizing the volume and weight of parts and materials to which energy is transferred	
3. Defaulting mechanisms to automatically reset the product to its most efficient setting	
4. Incorporating automatic or manual tuning capabilities.	

Significant Tradeoff Does Not Exist: Radiative heat flux decreases proportionally with the square of distance. If this design were to be used on two candidate solids, a thin slice of white bread and a thick bagel, the change in thickness is at most an inch. Assuming the bagel is 1” from the infrared coils and the bread is 2” away, the bread receives about ¼ the radiation of the bagel. It therefore seems that a large percentage of energy can be saved by reducing even an inch of space. The amount of extra material and manufacturing to create the expanding and contracting mechanisms will most likely not present a significant tradeoff.

D. IMPORT ENERGY

D.1 Place Weight

Control Group

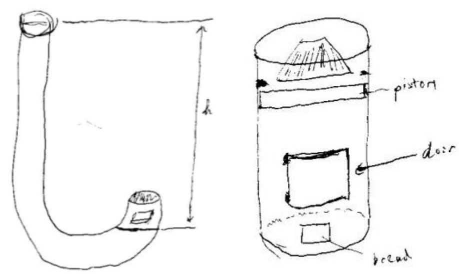


Figure I-7: Sketch of Place Weight

Viable: No

Explanation: It takes about 60kJ to toast bread at a medium – light setting. If the weight were 10lbs or approximately 50N (mangeable by a consumer) the weight would need to travel at least 1200 meters to impart 60kJ of work. If the water in the tube were 2ft, 0.61m, high, in a tube with a diameter slightly larger than the diagonal of a piece of bread, 6 inches or 0.15m, the weight of the water would be approximately 109 N and need to travel 550 meters to impart the necessary 60 kJ of work.

D.2 Attach to Fridge Coils

Control Group

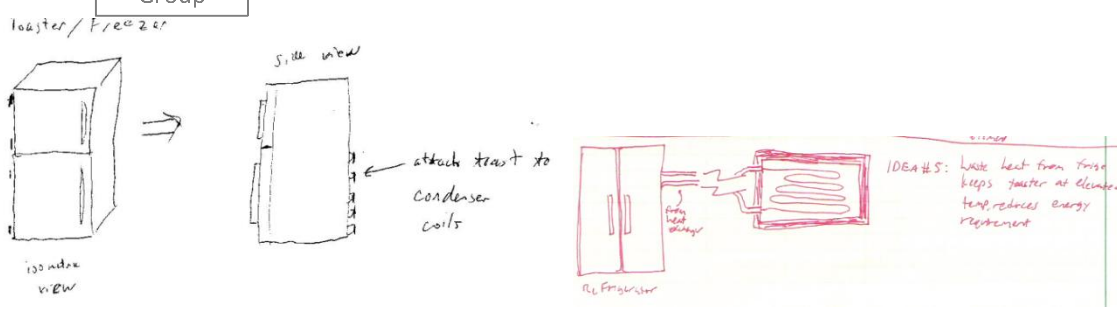


Figure I-8: Sketch of Attach to Refrigerator Coil

Viable: MAYBE

Explanation: It is conceivable that preheating or a base level of heat could be achieved by attaching the toaster to the heat exchange coils of a refrigerator. However, the compressor might need to be running. The measured temperature of a refrigerator coil is about 40˚C.
Practical: NO
Explanation: The idea would be feasible in homes where the refrigerator is next to open counter space where the toaster would be place. However, this set up is not universal and most cases would require an intrusive or complex system of plates or pipe connecting the refrigerator and the toaster that is deemed infeasible.

D.3 Attach to Car Engine

Control Group

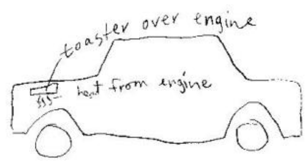


Figure I-9: Sketch of Attach to Car Engine

Practical: NO
Explanation: It is assumed that consumers want to toast in their kitchen before driving their car. Additionally control of toasting would be difficult for the consumer on the go.

D.4 Rotate Shaft by Wind

Control Group

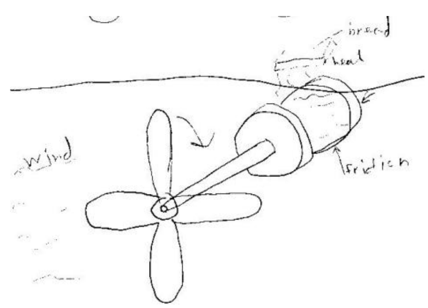


Figure I-10: Sketch of Rotate Shaft by Wind

Viable: YES
Explanation: A toaster operates at about 800W and requires approximately 60kJ to toast two slices of bread. Assuming that the toaster would have 2 m/s wind available to it (approx. 4 mph), the wind turbine would need sweep an area of 325m^2 (a radius of 10m) in order to create the available power without any efficiency losses.
Practical: NO
Explanation: A wind turbine that size does not fit in a residence.

D.5 Trap Solar Heat

Guidelines Group	Control Group

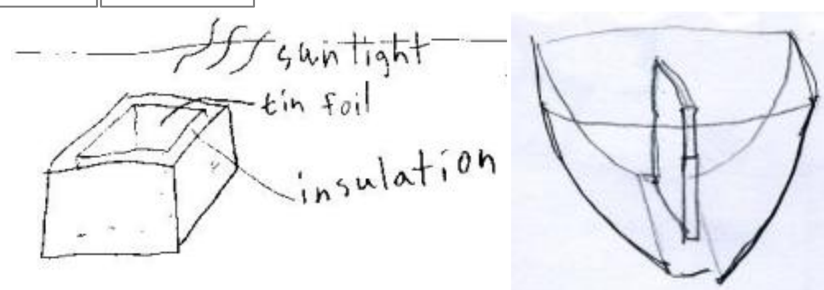


Figure I-11: Sketch of Trap Solar Heat

Viable: YES
Explanation: In Texas, there is an average of 4 kWh/m2 of solar insolation a day. In the north eastern United States, there is an average of 1.6 kWh/m2. Assuming that this energy is delivered evenly over a period of 12 hours, there is .14kW/m2 in the northeast and 0.32 kW/m2 in Texas. If the toast holds two slices of bread face down in the center, and has a perimeter of the width of one slice of bread, the area of insolation received is at most 0.24m2 (assuming 0.2m2 to be the area of a slice of bread.) To collect the necessary 60kJ, a solar thermal toaster would require 25 minutes of steady insolation in Texas and 60 minutes in the northeaster Unites States.
Practical: NO
Explanation: This range of 25-60 minutes is too long. Additionally, toast would usually be made at, before or soon after sunrise when solar heat is least available.

D.6 Power by Treadmill

Control Group

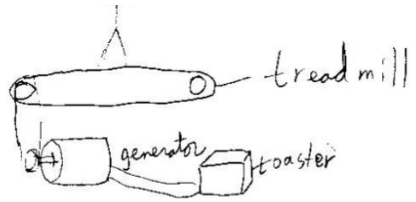


Figure I-12: Sketch of Power by Treadmill

Viable: YES
Explanation: Treadmills attached to DC generators are reported to be able to deliver 800W, the wattage of a basic toaster. [Gupta, 2009]
Practical: NO
Explanation: This design would require a person to own a treadmill as well as be able to use it. Treadmills do not fit in regular kitchens. The cost of a treadmill, generator, capacitor, and toaster would be beyond the $60 limit as well.

D.7 Collect Waste Burner Heat

Control Group

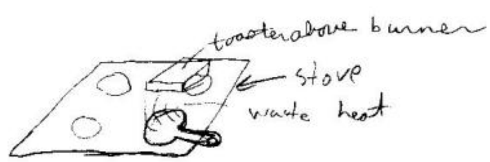


Figure I-13: Sketch of Collect Waste Burner Heat

Viable: NO
Explanation: In testing the waste heat from a stove top was not enough to toast bread. Additionally, waste heat could be in the form of steam that causes toast to become soggy.

D.8 Connect to Gas Tank

Control Group | Practical and Viable | Greener

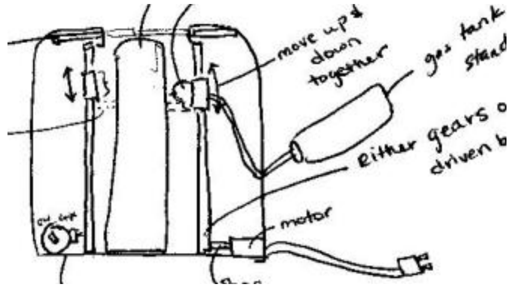


Figure I-14: Sketch of Connect to Gas Tank

Viable: YES
Explanation: Camping stoves work this way.
Practical: YES
Explanation: As long as safety precautions are met, there are no obvious deterrents to a gas tank of a small enough size.

Table I-7: Guidelines Corresponding to Connect to Gas Tank

Followed Guidelines	Violated Guidelines
1. Specifying best-in-class energy efficiency components.	No Change from Benchmark

Significant Tradeoff Does Not Exist: The energy source is more efficient without transmission and power plant losses. The effects of replacing or refilling the gas tank can be negligable if the tank is refilled (reused) infrequently.

D.9 Place Over Gas Burner

Guidelines Group | Practical and Viable | Greener

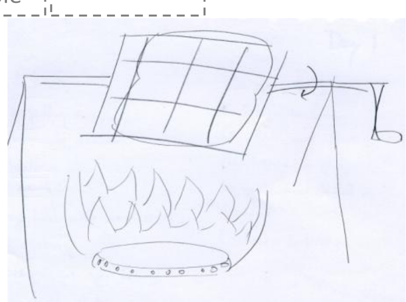


Figure I-15: Place over Gas Burner

Viable: YES
Explanation: Placing toast directly over a gas burner on high will toast bread in a few minutes, just like hamburger buns on a grill.
Practical: YES
Explanation: Requires a gas burner.

Table I-8: Guidelines Corresponding to Place over Gas Burner

Followed Guidelines	**Violated Guidelines**
1. Minimizing the number of components 2. Interconnecting available flows of energy and materials within the product or between the product and its environment	1. Implementing fail safes against heat and material loss 2. *Minimizing the quantity of resource use by optimizing its rate and duration.*

Significant Tradeoff Does Not Exist: The new design includes a more efficient energy source and requires significantly fewer components. No circuit boards, ceramics or wiring is needed. Though the effiiciency of the actual heating process is probably lower than that of a benchmark toaster, the source of energy for both could be natural gas. The efficiency of the power plant and transmission lines is most likely lower than the efficiency of the burner heating.

D.10 Crank Feed/Hand Crank

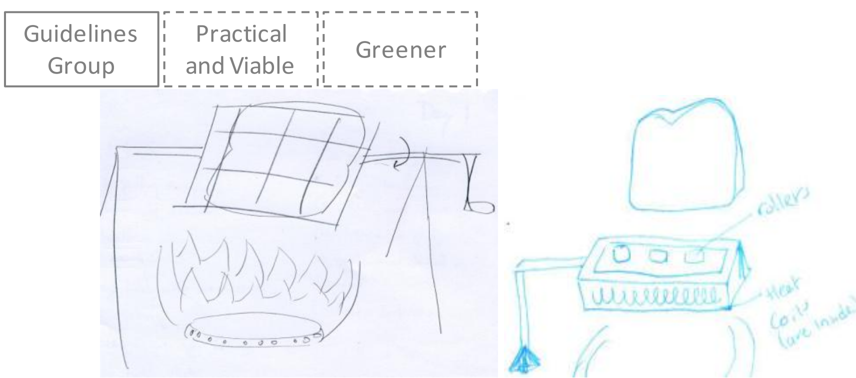


Figure I-16: Sketches of Hand Crank

Viable: YES
Explanation: There are no technical barriers to implementing a hand crank.
Practical: YES
Explanation: It is safe to handle and requires minimal effort for the designs proposed.

Table I-9: Guidelines Corresponding to Hand Crank

Followed Guidelines	Violated Guidelines
1. Specifying the cleanest source of energy 2. Minimizing the number of components	No Change from Benchmark

Significant Tradeoff Does Not Exist: The hand crank would replace a motorized component. A hand crank would reduce the electrical energy consumption of a new concept that has motion.

D.11 Store Solar Energy in Battery

Guidelines Group	Practical and Viable	Greener

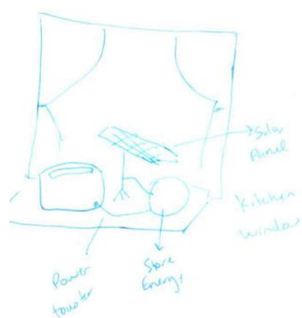


Figure I-17: Sketch of Store Solar Energy in Battery

Viable: YES
Explanation: In Texas, there is an average of 4 kWh/m2 of solar insolation a day. In the north eastern United States, there is an average of 1.6 kWh/m2. Assuming that the solar panel operates at 12% efficiency with full solar exposure, only about 0.006m2 of solar panel are required for Texas conditions, smaller than a piece of bread, and about 0.02m2 in the northeast, the size of a piece of bread. This calculation assumes no battery losses. The system would merely require the appropriate battery.
Practical: YES
Explanation: A rechargable battery that can deliver 800W and a solar panel reliable enough to charge the battery. The nominal cost would make the toaster moderately expensive, assuming $20 for the solar panel, $50 for the battery and $10 for the toaster at large scale manufacturing. This solution could be combined with an outlet cord as back up if the kitchen lacks solar exposure or is not able to obtain the required energy.

Table I-10: Guidelines Corresponding to Store Solar Energy in Battery

Followed Guidelines	Violated Guidelines
1. Specifying the cleanest source of energy	1. Minimizing the number of components 2. Specifying non-hazardous and otherwise environmentally “clean” substances, especially in regards to user health

Significant Tradeoff Does Not Exist: The environmental impact of the manufacturing of the toaster would be dominated by the battery and solar panel, but a significant amount of energy would be saved. Payback on the energy to make a solar panel is estimated at 4 years. Therefore, the trade-off of energy savings and high-impact components could become even no sooner than 4 years for the solar panel and even longer when adding the environmental cost of the battery. Stevels *et al.* concluded from LCAs of differently powered radios that the impact of batteries depends on how they are disposed [Stevels, JSPD]. Assuming that the toaster is mostly solar powered over a ten year life span and the batteries are fully recycled, the environmental impact of a solar toaster could be lower than a benchmark plug-in toaster.

D.12 Shake solenoid

Guidelines Group

Figure I-18: Sketch of Shake Solenoid

Viable: NO
Explanation: Assuming one shake per second, a distance the length of a wii mote (0.2m) and a weight of about 18N (4 lbs), the solenoid cannot produce more than 3.6 Joules per second.

D.13 Insert Thermal Mass

Guidelines Group | Practical and Viable | Greener

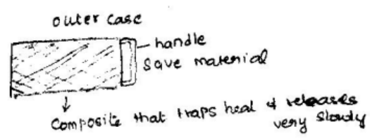


Figure I-19: Sketch of Insert Thermal Mass

Viable: YES
Explanation: Thermal masses can be used to store large amounts of heat and let it out slowly, providing insulation and preheating.
Practical: YES
Explanation: The thermal mass does not have to be used by the consumer, but could be used to absorb heat from an oven or dishwasher after use and be easily inserted.

Table I-11: Guidelines Corresponding to Insert Thermal Mass

Followed Guidelines	Violated Guidelines
1. Specifying the cleanest source of energy 2. Interconnecting available flows of energy and materials within the product or between the product and its environment	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: If the thermal mass were used to collect heat waste heat from a refrigerator or cool down an oven or dishwasher quickly, it could help increase the the efficiency of the refrigerator or home climate as well as minimize the amount of fan cooling needed for an oven.If the thermal mass can then be used to preheat or insulate a toaster, it would save further energy. The impacts of creating the thermal mass element could be high, depending on the source. Cement has high-embedded energy. Some phase change materials can be organic and have lower impact. The exact tradeoffs would depend upon the embodiment and requires that the thermal mass is utilized. It is most likely that the thermal mass would not be used for the toaster, but could provide functions in other device. It cannot be determined that a an increase in environmental impact would result from this feature.

D.14 Contain Fuel Cell

Guidelines Group

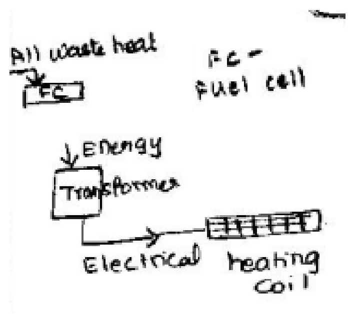


Figure I-20: Sketch of Contain Fuel Cell

Viable: NO
Explanation: Current small fuel cells do exist. However, fuel cells that can be used in the home usually require a solar panel to make hyrdogen from water. These small fuel cells, such as those for RC cars, produce about 1-30W of power [80]. These are much less than the 800W required for a toaster. Other home fuel cells that use feedstocks such as methanol or ethanol aren't readily available.
Practical: NO
Explanation: Currently hydrogen fuel cell kits and cars cost between \$100-\$1500. A toaster with a 1W fuel cell would be within current range of prices for toasters on the market, but a 30W cell would be well outside of the cost range.

D.15 Connect to Hot Water Lines

Guidelines Group

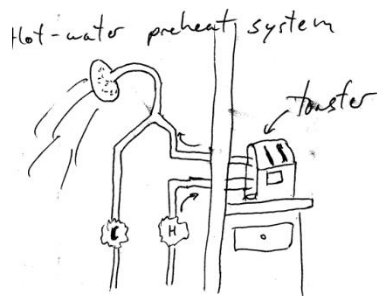


Figure I-21: Sketch of Connect to Hot Water Lines

Viable: YES
Explanation: It could be possible to create thick, water tight, walls in the toaster and connect it to the water system.
Practical: NO

Explanation: This design does not integrate with daily, kitchen routine of an average residence. It requires cumbersome, connection to existing hot water systems and requires that the water in the pipe is hot, something that isn't true unless the water is running or there is a tank and boiler system.

D.16 Insert in Coffee Maker

Guidelines Group	Practical and Viable	Greener

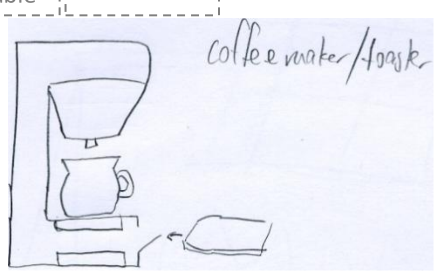


Figure I-22: Sketches of Insert in Coffee Maker

Viable: YES
Explanation: The hot plate that heats coffee water and keeps it warm could also be used to toast bread while keeping the coffee warm.
Practical: Yes.
Explanation: Toaster and coffee maker combination appliances are marketed and sold.

Table I-12: Guidelines Corresponding to Insert in Coffee Maker

Followed Guidelines	Violated Guidelines
1. Minimizing the number of components 2. Interconnecting available flows of energy and materials within the product or between the product and its environment	No Change from Benchmark

Significant Tradeoff Does Not Exist: By sharing components, the combined coffee maker and toaster reduce the environmental impact of components. If the waste heat of the toaster is used to warm coffee or vice versa, the efficiency of energy used is increased.

E. CONVERT ENERGY TO THERMAL ENERGY

E.1 Burn Natural Gas

Control Group	Practical and Viable	Greener

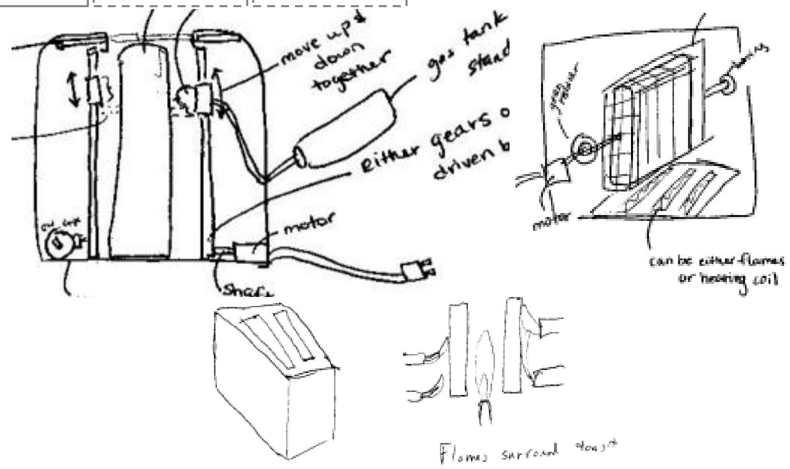


Figure I-23: Sketches of Burn Natural Gas

Viable: YES
Explanation: Operates like existing gas stoves or ovens.
Practical: YES
Explanation: Many consumers own gas heated appliances.

Table I-13: Guidelines Corresponding to Burn Natural Gas

Followed Guidelines	Violated Guidelines
1. Specifying best-in-class energy efficient components	No Change from Benchmark

Significant Tradeoff Does Not Exist: Creating a gas burning toaster does not require many more components than an electrical toaster. It could be more efficient as it is a more direct source of energy than electricity from the grid.

E.2 Rub Friction Material

Guidelines Group	Control Group

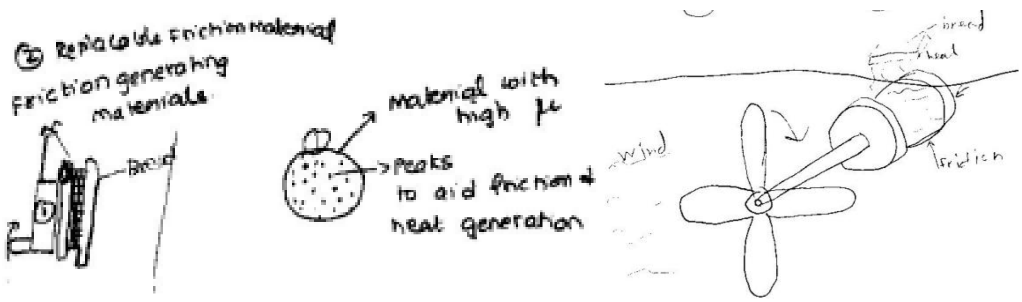


Figure I-24: Sketches of Rub Friction Material

Viable: NO
Explanation: In order to produce the necessary 800 W of heat, an extremely frictional material will be needed, assume a coefficient of friction of 2. The material would need to be pressed in excess of 1000 and rubbed so fast that it travels 1m/s.

E.3 Heat with Resistive Plate

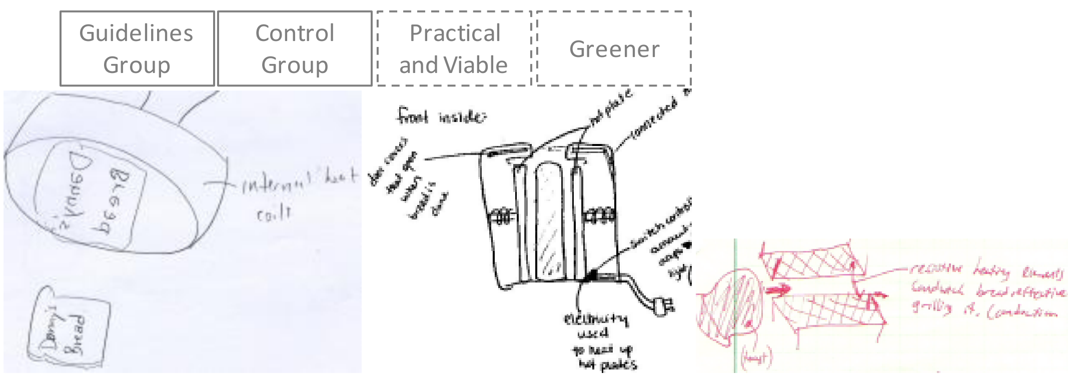


Figure I-25: Sketches of Heat with Resistive Plate

Viable: YES
Explanation: Resistive heating plates exist.
Practical: YES
Explanation: George Foreman grills are popular and operate with two heated grill plates.

Table I-14: Guidelines Corresponding to Heat with Resistive Plate

Followed Guidelines	**Violated Guidelines**
No Change from Benchmark	No Change from Benchmark

E.4 Heat with Infrared

Guidelines Group | Control Group | Practical and Viable | Greener

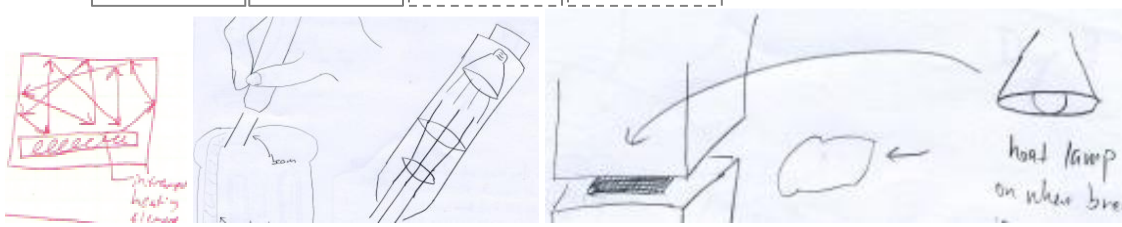


Figure I-26: Sketches of Heat with Infrared

Viable: YES
Explanation: Toasters currently use infrared coils.
Practical: YES
Explanation: Toasters currently use infrared coils.

Table I-15: Guidelines Corresponding to Heat with Infrared

Followed Guidelines	Violated Guidelines
No Change from Benchmark	No Change from Benchmark

E.5 Compress Gas/Air in Cylinder

Control Group

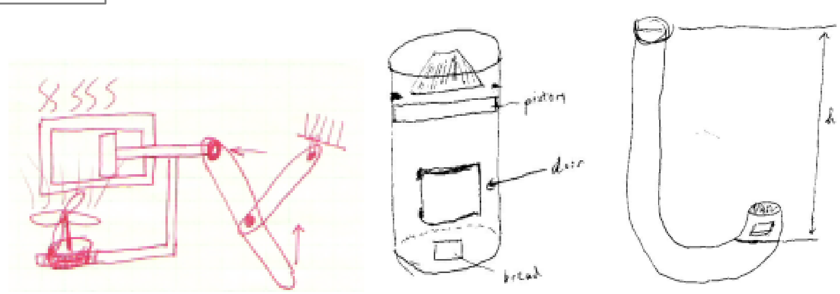


Figure I-27: Sketches of Compress Gas in Cylinder

Viable: No
Explanation: It takes about 60kJ to toast bread at a medium – light setting. If the weight were 10lbs or approximately 50N (mangeable by a consumer) the weight would need to travel at least 1200 meters to impart 60kJ of work. Limiting the distance to 0.5m, it would require 120kN of force. This calculation assumes all the input work turns into heat.

E.6 Heat Resistively (balance radiation + convection)

Guidelines Group	Practical and Viable	Greener

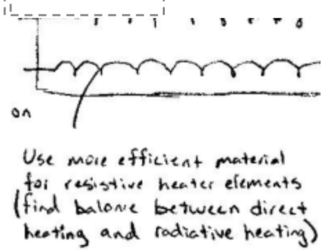


Figure I-28: Description of Heat Resistively

Viable: YES
Explanation: Current technology in benchmark solution. Requires necessary work to optimize the coil material within bounds of current technology.
Practical: YES
Explanation: Current solution.

Table I-16: Guidelines Corresponding to Heat Resistively

Followed Guidelines	Violated Guidelines
1. Specifying best-in-class energy efficiency components	No Change from Benchmark

Significant Tradeoff Does Not Exist: This solution may be different from the current solution, if the current coils are not optimally balanced.

F. Transfer Thermal Energy to Solid

F.1 Touch/Stamp Bread with Hot Plate

Guidelines Group	Control Group	Practical and Viable	Greener

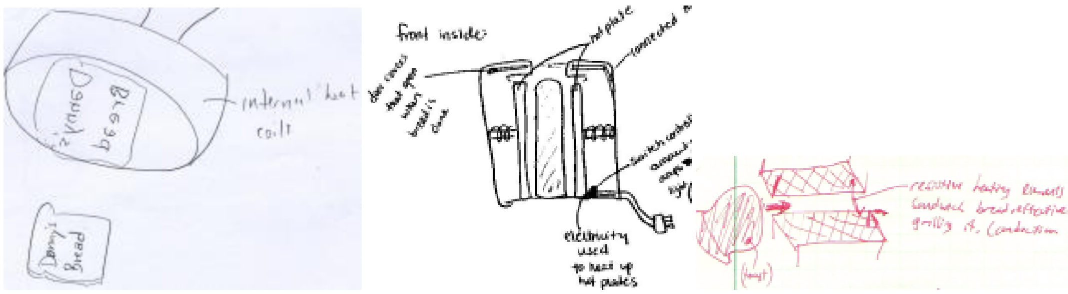


Figure I-29: Sketches of Stamp Bread with Hot Plate

Viable: YES
Explanation: Technology operates like a panini maker.
Practical: YES
Explanation: Idea is similar to current panini makers.

Table I-17: Guidelines Corresponding to Stamp Bread with Hot Plate

Followed Guidelines	Violated Guidelines
No Change from Benchmark	No Change from Benchmark

G. GUIDE TE

G.1 Reflect Radiation

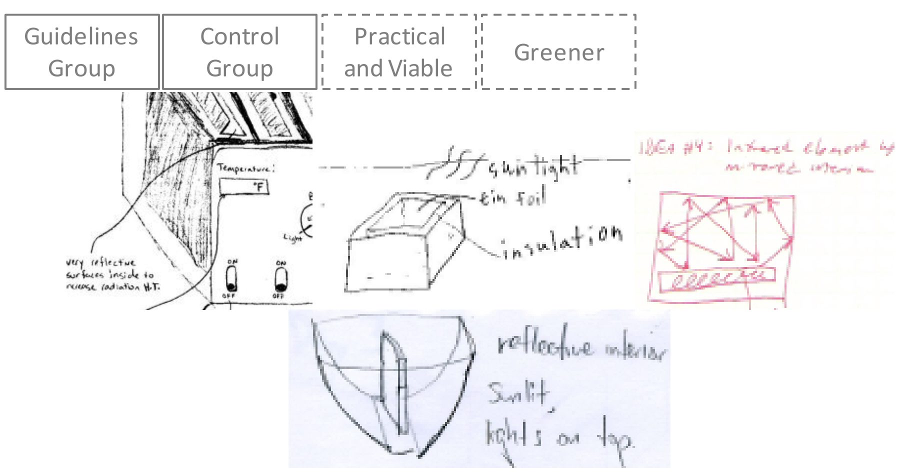


Figure I-30: Sketches of Reflect Radiation

Viable: YES

Explanation: Mirror surfaces or surface with high reflectivity will reflect radiation well enough to provide insulation..
Practical: YES
Explanation: Idea has no logistical limitations.

Table I-18: Guidelines Corresponding to Reflect Radiation

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	No Change in Guidelines

Significant Tradeoff Does Not Exist: A mirror surface could provide better insulation and higher power than the current mica ceramic in toasters. The different environmental impacts of the materials are not known.

G.2 Move Heat Source Vertically

Control Group | Practical and Viable

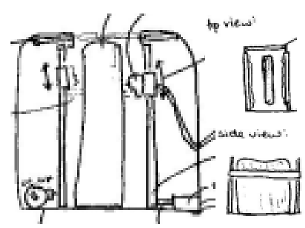


Figure I-31: Sketch of Move Heat Source Vertically

Viable: YES
Explanation: Moving an electrical heater is possible. Moving flames that are small enough to be in the toaster would most likely put them out. If the movement rate is limited it could be viable.
Practical: YES
Explanation: The idea has no use or excessive cost limitations.

Table I-19: Guidelines Corresponding to Move Heat Source Vertically

Followed Guidelines	Violated Guidelines
No Change from Benchmark	1. Minimizing the number of components

Significant Tradeoff Does Exist: The device would reduce the amount of coils or burners, but would also require addition of a motor and gears and increased electricity use from the motor. A hand crank could be used, the tradeoff between components is not clear but will likely yield no net improvement.

G. 3 Rotate Bread Cage

Guidelines Group | Control Group | Practical and Viable

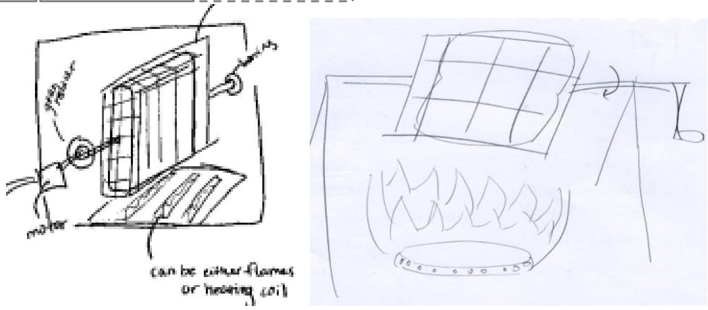


Figure I-32: Sketches of Rotate Bread Cage

Viable: YES
Explanation: Works like a roaster and can provide even heating.
Practical: YES
Explanation: Idea is similar to a roaster. It could be motorized or hand powered.

Table I-20: Guidelines Corresponding to Rotate Bread Cage

Followed Guidelines	Violated Guidelines
1. Minimizing the number of components	1. Implementing fail safes against heat and material loss

Significant Tradeoff Does Exist: The device could reduce the amount of coils or burners if heater is only on one side. However it could also double the heating time and amount of energy used. The component savings are most likely not comparable to the increased energy use.

G.4 Intensify Inner Coil

Guidelines Group | Practical and Viable

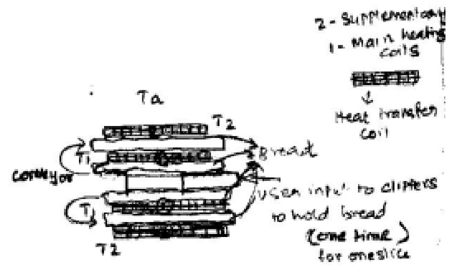


Figure I-33: Sketch of Intensify Inner Coil

Viable: YES
Explanation: It is possible to make the inner coil between two slots release more heat.
Practical: YES
Explanation: This idea only requires that the use be able to flip the bread so that the hotter coil toasts and the cooler coil keeps the bread warm.

Table I-21: Guidelines Corresponding to Intensify Inner Coil

Followed Guidelines	Violated Guidelines
No Change in Guidelines	No Change in Guidelines

G.5 Blow Heat

Guidelines Group | Control Group | Practical and Viable | Greener

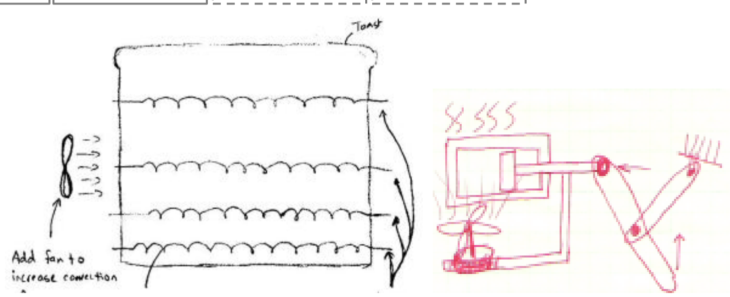


Figure I-34: Sketches of Blow Heat

Viable: YES
Explanation: Convection ovens use fans to reduce heating temperature but transfer heat more quickly.
Practical: YES

Explanation: A convection oven could be used for toasting.

Table I-22: Guidelines Corresponding to Blow Heat

Followed Guidelines	Violated Guidelines
1. *Minimizing the quantity of resource use by optimizing between its rate and duration.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: Convection ovens use a fan to bake at lower temperature more quickly. It is not certain that the addition of a fan to a toaster will make it more efficient. Addition of a fan will require additional energy to power the fan and manufacturing to create the fan. It is most likely that a toaster's environmental impact does not benefit from a fan.

G.6 Scan Bread

Guidelines Group	Practical and Viable	Greener

Figure I-35: Sketch of Scan Bread

Viable: YES
Explanation: The bread does not need to be toasted evenly at the same time. It can be toasted by increments of length.
Practical: YES
Explanation: The user might need to monitor the process if it is hand cranked, but it can be completely automated by use of a motor. The design requires a support, but will have a smaller kitchen footprint.

Table I-23: Guidelines Corresponding to Scan Bread

Followed Guidelines	Violated Guidelines
1. Minimizing the number of components 2. Minimizing the volume and weight of parts	1. Implementing fail safes against heat and material loss

and materials to which energy is transferred

Significant Tradeoff Does Not Exist: This feature requires fewer materials and performs the same task. It may or may not save energy during the use phase: The amount of area heated will be closer to the bread inserted, but the duration and the intensity of the heating will have to be such that the bottom of the bread does not cool before the top of the bread is toasted.

G.7 Locate more heating elements at bottom

Guidelines Group	Practical and Viable

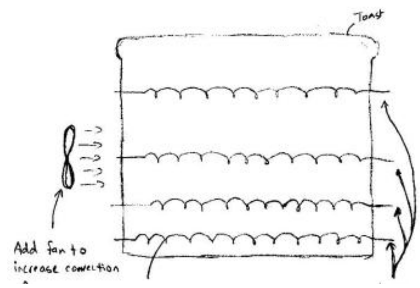


Figure I-36: Sketch of Locate More Heating Elements at Bottom

Viable: YES
Explanation: There is no technical limitation to moving the location of the heating elements. The locations would need to coordinated with rising convection in order to evenly toast the bread.
Practical: YES
Explanation: The idea has no use or excessive cost limitations.

Table I-24: Guidelines Corresponding to Locate More Heating Elements at Bottom

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	1. Specifying best-in-class energy efficient components

Significant Tradeoff Does Exist: This feature requires a primarily convective heating solution to provide impact. Though It does not require any additional parts or environmental impact compared to a benchmark toaster, convective toasting in with vertical coils is less efficient than radiative. This design will most likely have a slightly higher impact.

G.8 Manually Trace Bread Surface

Guidelines Group | Practical and Viable

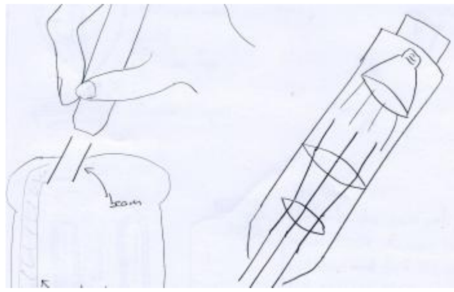


Figure I-37: Sketch of Manually Trace Bread

Viable: YES
Explanation: There is no technical limitation to moving the location of the heating elements. The locations would need to coordinated with rising convection in order to evenly toast the bread.
Practical: YES
Explanation: The idea has no use or excessive cost limitations.

Table I-25: Guidelines Corresponding to Manually Trace Bread

Followed Guidelines	**Violated Guidelines**
1. Minimizing the number of components 2. Minimizing the volume and weight of parts and materials to which energy is transferred *3. Incorporating automatic or manual tuning capabilities.*	1. Implementing fail safes against heat and material loss

Significant Tradeoff Does Exist: This feature requires fewer materials and performs the same task. It may not save energy during the use phase: The amount of area will be equal to the surface of the toast, but the area heated will be small and unenclosed, allowing more heat loss from human error and reuse due to uneven heating and cooling of the toast.

H. STOP THERMAL ENERGY

H.1 Minimize Space

Guidelines Group	Control Group	Practical and Viable	Greener

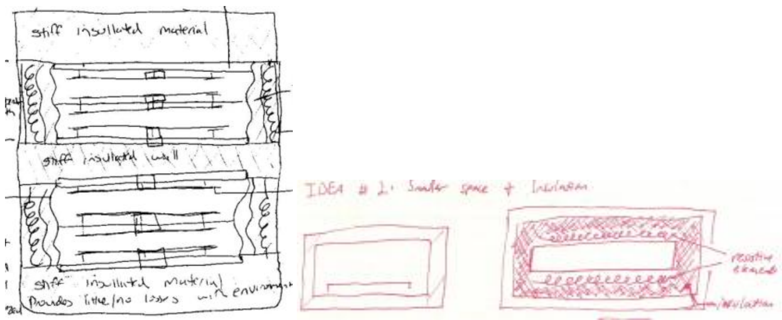


Figure I-38: Sketches of Minimize Space

Viable: YES
Explanation: There are no technical barriers to minimizing geometry.
Practical: YES
Explanation: The idea has no use or excessive cost limitations.

Table I-26: Guidelines Corresponding to Minimize Space

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss 2. Minimizing the volume and weight of parts and materials to which energy is transferred	

Significant Tradeoff Does Not Exist: This feature requires fewer materials and performs the same task. It may not save energy during the use phase: The amount of area will be equal to the surface of the toast, but the area heated will be small and unenclosed, allowing more heat loss from human error and reuse due to uneven heating and cooling of the toast.

H.2 Cover Slot

Guidelines Group	Control Group	Practical and Viable	Greener

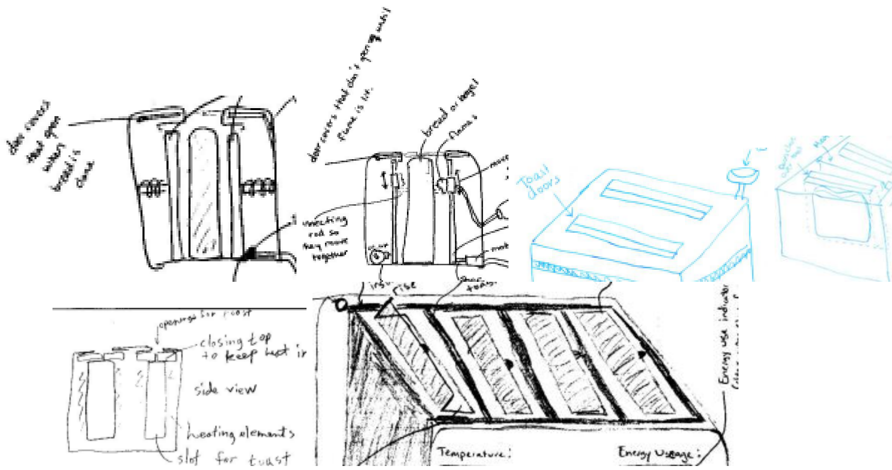


Figure I-39: Sketches of Cover Slot

Viable: YES

Explanation: There are no technical barriers to adding a cover. This idea is currently used in commercial toasters.

Practical: YES

Explanation: The use can manually cover the slot or it can be manual. There would need to be a heat guarded mechanism for opening and closing so that the user isn't burtned.

Table I-27: Guidelines Corresponding to Cover Slot

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	1. Minimizing the number of components

Significant Tradeoff Does Exist: This feature has an almost negligable increase in the number of components and assured reduction of energy loss.

H.3 Seal Compartment

Guidelines Group	Control Group	Practical and Viable	Greener

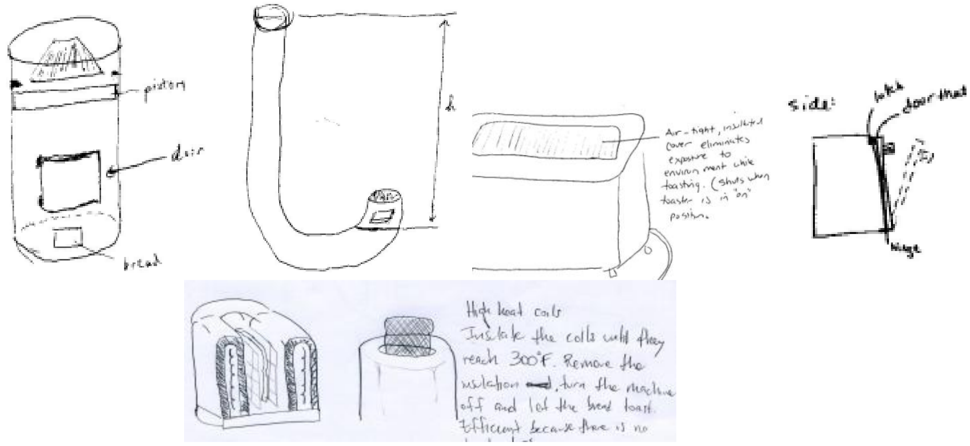


Figure I-40: Sketches of Seal Compartment

Viable: YES
Explanation: There are no technical barriers to sealing a heating compartment. It is currently done in toaster ovens and ovens.
Practical: YES
Explanation: There would need to be a heat guarded mechanism for opening and closing so that the user isn't burtned.

Table I-28: Guidelines Corresponding to Seal Compartment

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	1. Minimizing the number of components

Significant Tradeoff Does Exist: This feature has an almost negligable increase in the number of components and assured reduction of energy loss.

H.4 Combine Slices in One Slot

Guidelines Group | Practical and Viable | Greener

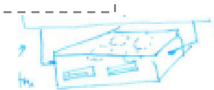


Figure I-41: Sketch of Combine Slices in One Slot

Viable: YES

Explanation: Just requires a larger toaster slot.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-29: Guidelines Corresponding to Combine Slices in One Slot

Followed Guidelines	Violated Guidelines
No Change from Benchmark	No Change from Benchmark

H.5 Insulate Interior

Guidelines Group | Control Group | Practical and Viable | Greener

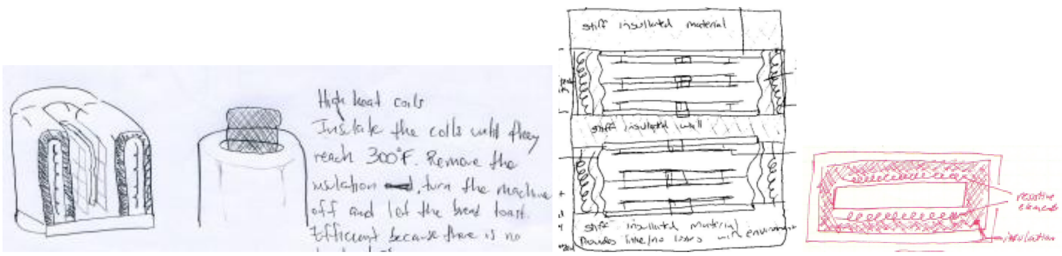


Figure I-42: Sketches of Insulate Interior

Viable: YES
Explanation: Insulation is commonly used in heating devices.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-30: Guidelines Corresponding to Insulate Interior

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	1. Minimizing the number of components

H.6 Insulate with Water

Guidelines Group | Practical and Viable | Greener

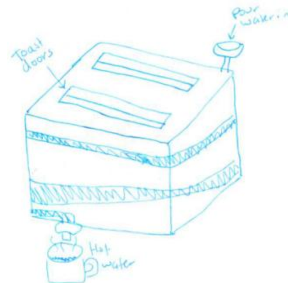


Figure I-43: Sketch of Insulate With Water

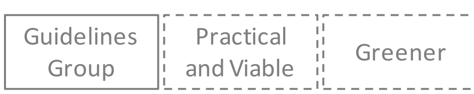
Viable: YES
Explanation: The water would serve as a thermal mass, absorbing energy rather than insulating. However, the idea could be used to heat water with toaster waste heat.
Practical: YES
Explanation: Tea and toast are often made together.

Table I-31: Guidelines Corresponding to Insulate with Water

Followed Guidelines	Violated Guidelines
1. Interconnecting available flows of energy and materials within the product or between the product and its environment	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: By sharing components, the combined hot water and toaster reduce the environmental impact of heating water. Few components for taps and water channels would be needed.

H.7 Separate Unused Slots



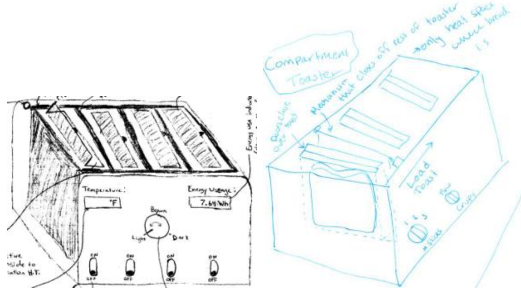


Figure I-44: Sketches of Separate Unused Slots

Viable: YES
Explanation: Just requires separate construction.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-32: Guidelines Corresponding to Separate Unused Slots

Followed Guidelines	Violated Guidelines
1. Implementing default power down for subsystems that are not in use 2. Implementing fail safes against heat and material loss 3. Minimizing the volume and weight of parts and materials to which energy is transferred *4. Creating separate modules for tasks with conflicting requirements or solutions*	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: A small, two slot toaster heats both slots every use. If only one is being used, separating slots contains the heat energy more effectively.

H.8 Insulate with Thermal Mass

Guidelines Group	Practical and Viable	Greener

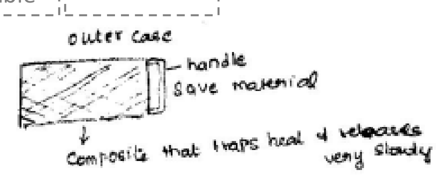


Figure I-45: Sketch of Insulate With Thermal Mass

Viable: YES
Explanation: Thermal masses can be used to store large amounts of heat and let it out slowly, providing insulation and preheating.
Practical: YES
Explanation: The thermal mass does not have to be used by the consumer, but could be used to absorb heat from an oven or dishwasher after use and be easily inserted.

Table I-33: Guidelines Corresponding to Insulate with Thermal Mass

Followed Guidelines	Violated Guidelines
1. Specifying the cleanest source of energy	2. Minimizing the number of components
2. Interconnecting available flows of energy and materials within the product or between the product and its environment	
3. Creating separate modules for tasks with conflicting requirements or solutions	

Significant Tradeoff Does Not Exist: Waste heat could be taken from other sources, insulating the toaster with this waste heat could provide pre-heat and better insulation. The module could also be used for other heating needs and its useful life would likely outlast the life of the toaster.

H.9 Insulate with Hot Water

Guidelines Group

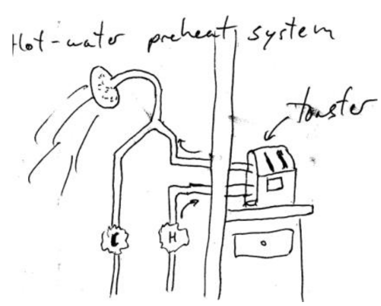


Figure I-46: Sketch of Insulate With Hot Water

Viable: YES
Explanation: It could be possible to create thick, water tight, walls in the toaster and connect it to the water system. It is possible that the water might start boiling away.
Practical: NO
Explanation: It would need access to hot water. The water boiling and increase pressure could cause rupture.

H.10 Insulate Top More

Guidelines Group | Practical and Viable | Greener

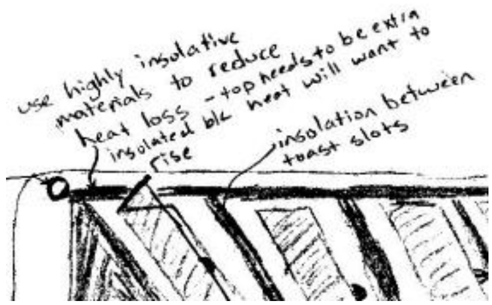


Figure I-47: Sketch of Insulate Top More

Viable: YES
Explanation: Insulation is commonly used in heating devices.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-34: Guidelines Corresponding to Insulate Top More

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss *2. Creating separate modules for tasks with conflicting requirements or solutions*	1. Minimizing the number of components

Significant Tradeoff Does Not Exist: Insulating the top is not a large area. The improvement may be negligable, but so might the extra material and production.

H.11 Insert through Horizontal Slot

Guidelines Group | Control Group | Practical and Viable | Greener

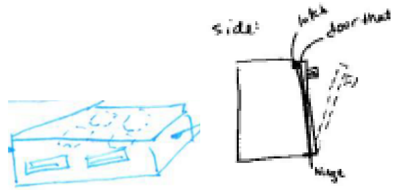


Figure I-48: Sketches of Insert through Horizontal Slot

Viable: YES
Explanation: No technical limitations to a new geometry. Horizontal openings are used for ovens.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-35: Guidelines Corresponding to Insert through Horizontal Slot

Followed Guidelines	Violated Guidelines
1. Implementing fail safes against heat and material loss	No Change from Benchmark

I. Display Signal

I.1 Indicate Energy Use

Guidelines Group | Practical and Viable

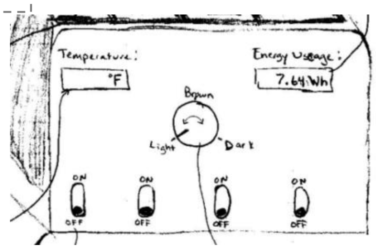


Figure I-49: Sketch of Indicate Energy Use

Viable: YES
Explanation: It is possible to add a power meter and display.
Practical: YES

Explanation: The feature has no use or excessive cost limitations.

Table I-36: Guidelines Corresponding to Indicate Energy Use

Followed Guidelines	Violated Guidelines
1. Use feedack mechanisms to indicate how much energy or water is being consumed 2. *Using feedback mechanisms to inform the user of the current status of the process.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: It is not clear how energy feedback to the user can help save energy.

I.2 Indicate Temperature

Guidelines Group | Practical and Viable

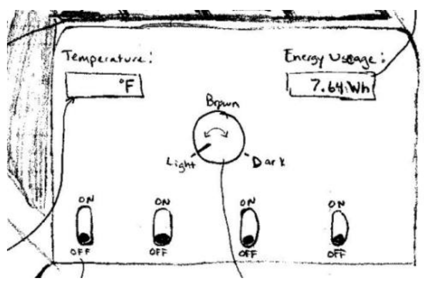


Figure I-50: Sketch of Indicate Temperature

Viable: YES
Explanation: It is possible to add a temperature meter and display.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-37: Guidelines Corresponding to Indicate Temperature

Followed Guidelines	Violated Guidelines
1. *Using feedback mechanisms to inform the user of the current status of the process.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: It is not clear how temperature feedback to the user can help save energy.

I.3 Light when on

Control Group	Practical and Viable

Figure I-51: Sketch of Light When On

Viable: YES
Explanation: It is possible to add an on light.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-38: Guidelines Corresponding to Light When On

Followed Guidelines	Violated Guidelines
1. *Using feedback mechanisms to inform the user of the current status of the process.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: No foreseeable energy savings.

I.4 Light when done

Guidelines Group	Practical and Viable

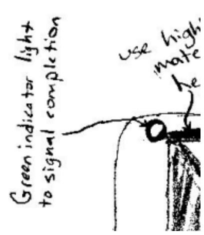


Figure I-52: Sketch of Light When Done

Viable: YES
Explanation: It is possible to add a light and a circuit that turns it on after heating.
Practical: YES
Explanation: The feature has no use or excessive cost limitations.

Table I-39: Guidelines Corresponding to Light When Done

Followed Guidelines	Violated Guidelines
1. *Using feedback mechanisms to inform the user of the current status of the process.*	1. Minimizing the number of components

Significant Tradeoff Does Exist: No foreseeable energy savings.

I.5 Play Wii Game

Guidelines Group

Figure I-53: Sketch of Play Wii Game

Viable: YES
Explanation: It is possible to connect a Wii to other modern appliances and create a game interface.
Practical: NO
Explanation: Not everyone has a Wii and the activities of toasting bread and playing Wii do not often happen concurrently.

References

[1] Minnesota House of Representatives, 2007, "H.F. No. 854, 5th Engrossment - 85th Legislative Session (2007-2008)," https://www.revisor.mn.gov/bin/bldbill.php?bill=H0854.5.html&session=ls85; Accessed: July 2009.

[2] Electronics Take-Back Coalition, "Who takes back?," http://www.computertakeback.com/corporate/who_takes_back.htm; Accessed: July 2009.

[3] Toffel, M. W., 2003, "The Growing Strategic Importance of End-of-Life Product Management," California Management Review, 45(3).

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