ABSTRACT

Title of Document: **ENVIRONMENTAL OPPORTUNITIES IN CONCEPTUAL DESIGN: ENHANCING THE TRIZ DATABASE WITH ENERGY STAR PRODUCTS AND FUNCTIONAL MODELS**

David Christopher Morgan, Masters of Science in Mechanical Engineering, 2007

Directed By: Dr. Linda Schmidt, Department of Mechanical Engineering

Engineers use the product design process is to create new products. This process begins with a problem statement and conceptual design and concludes with the embodiment design phase, where the details of the product are formed and final designs are created. There are efforts being made to increase awareness of the impact of the decisions made in this process with respect to the environment. Currently, environmental design is done in the embodiment phase, far into the design process and after a concept is selected. This paper focuses on a method to consider environmental design during concept generation.

This research will show how environmental products can be incorporated into the TRIZ database (in English, TIPS – Theory of Inventive Problem Solving). TRIZ is an organized and advanced form of design by analogy and is based on overcoming contradictions between a set of engineering parameters. TRIZ provides innovative principles that are linked to a repository of patents and products.

The fundamental research question for the basis of this work is: Can the TRIZ method be expanded for the design team that places high value on environmentally benign designs? This can be broken down into more specific questions. Question One: How do you find products to expand the TRIZ database specifically so that it can be more useful for environmentally benign design changes? Question Two: How can function structures be used to catalog environmental innovations and aid in applying TRIZ principles? This work will demonstrate how this expansion of TRIZ can be accomplished and will yield three unique contributions.

There are three contributions to this work. Contribution One is the analysis of the relative frequency of TRIZ principles for combinations of engineering characteristics within the TRIZ contradiction matrix. Contribution Two is the use of function models, according to the function basis to characterize technical performance contradictions in terms of TRIZ engineering characteristics and to identify environmental innovations in

existing designs. Contribution Three is providing support for the validity of expanding the TRIZ database using certified green products and functional modeling. This will be demonstrated by examining electrical energy saving household appliances, and detailing the process by which they can be added to the TRIZ database.

ENVIRONMENTAL OPPORTUNITIES IN CONCEPTUAL DESIGN: ENHANCING THE TRIZ DATABASE WITH ENERGY STAR PRODUCTS AND FUNCTIONAL MODELS

By
David Christopher Morgan

Thesis submitted to the Faculty of the Graduate School of the University of Maryland, college Park in partial fulfillment Of the requirements for the degree of Masters of Science
2007

Primary Advisor: Dr. Linda Schmidt
Co-Advisor: Dr. Jeffrey Herrmann
Committee Member: Dr. Avram Bar-Cohen

Acknowledgements

I would like to thank my family and friends for their support during these interesting years. I would also like to thank my Advisor, Dr. Linda Schmidt for her guidance and above all patience with my antics. Finally I would like to thank my wife, Mary for her commitment and motivation.

Table of Contents:

Prelude 1

1 Introduction 3
1.1 Environmental Design Example 4
1.2 First Generation Environmental Design Strategies 6
1.3 Next Generation Environmental Design Strategies 6
1.4 Research Questions 8
1.5 Organization of Thesis 8

2 Background 10
2.1 Product Design Process 10
2.2 Design for Environment 13
2.3 Functional Models 16
2.4 TRIZ 19
2.5 Environmental TRIZ 23
2.6 Industry Trends 25

3 Creating a Method for the TRIZ Database Expansion 30
3.1 Definition of "Green" Products 30
3.2 Search Strategy Proposal One: Product Search 31
3.3 Search Strategy 2: Analyzing the Existing TRIZ Database 33
3.4 The Application of Search Strategies 35

4 Analysis of TRIZ Engineering Characteristics 38

5 Analysis of TRIZ Principles 41
5.1 Frequency of 40 Principles in TRIZ Matrix 43
5.2 Frequency of 40 Principles with respect to Environmental Contradictions 46
5.3 Frequency of 40 TRIZ Principles with respect to Energy Contradictions 48

6 ENERGY STAR 50
6.1 ENERGY STAR Categories 52
6.2 ENERGY STAR Appliances Category 53
6.3 ENERGY STAR Dishwashers 54
6.3.1 Kenmore Dishwashers 56
6.3.2 Bosch Dishwashers 57
6.4 ENERGY STAR Refrigerators and Freezers 58
6.5 ENERGY STAR Clothes Washers 59
6.6 ENERGY STAR Room Air Conditioners 60
6.7 ENERGY STAR Dehumidifiers 61

7 Using Functional Models to Identify Design Contradictions 63
7.1 ENERGY STAR Appliance Functional Decomposition 63
7.2 Energy Related Conceptual Design Opportunities Using TRIZ 67
7.3 Using Expanded TRIZ Database for Conceptual Design 70

8 Contributions and Future Work ... 73
8.1 Contributions ... 74
8.2 Future Work ... 75

Appendix A: TRIZ Contradiction Matrix ... 77

Appendix B: EEC and WBSCD Category Comparison ... 78

Appendix C: Function Models ... 82

Appendix D: Additional Information for ENERGY STAR Database [2] ... 86

9 References ... 93

List of Tables:

Table 1: Example of primary and secondary functional classes [24] 18
Table 2: Example of primary and secondary functional flows [24] 18
Table 3: Foundations of TRIZ [16].. 22
Table 4: TRIZ patterns of Evolution [16] 23
Table 5: Relationship of TRIZ ECs with World Business Council for Sustainable Development eco-efficiency categories [19, 26] 25
Table 6: PDP Category matrix that shows the categories to which each EEC belongs.... 79
Table 7: Comparison Matrix of Environmental Categories Proposed and WBSCD [18, 19] 81
Table 8: ENERGY STAR Metrics for Room Air Conditioners 86
Table 9: ENERGY STAR Metrics for Dehumidifiers 88
Table 10: ENERGY STAR Metrics for Clothes Washers 89
Table 11: ENERGY STAR Metrics for Dishwashers... 90
Table 12: Company, Product and Patent Information for ENERGY STAR Database..... 91
Table 13: Portion of ENERGY STAR Database for Kenmore Dishwashers 92

List of Figures:

Figure 1: Schematic of Product Development Process [4] 10
Figure 2: Generic representation of a product's Life-Cycle from cradle to grave and reincarnation [12].. 12
Figure 3: Example of Eco-Compass[13].. 15
Figure 4: Environmental Category Comparison of WBCSD and Eco-Compass 16
Figure 5: Function model of household portable room heater [24] 19
Figure 6: Triple Bottom Line 27
Figure 7: Examples of Six-Sigma variation plots showing an off target process (upper left), wide variation from target (upper right) and the ideal scenario (bottom middle) [33]. 28
Figure 8: Search Strategy Proposal One: Environmental Product Search 33
Figure 9: Search Strategy Proposal Two: Searching Existing TRIZ database for Environmental Innovations 35
Figure 10: Organizational flow diagram 37
Figure 11: Snapshot of TRIZ matrix engineering characteristics 1 through 8 and intersecting cells with numbers corresponding to 40 TRIZ principles [1] 41
Figure 12: Example of chart showing frequency of 40 TRIZ principles with respect to EC1: Weight of Mobile Object. 43
Figure 13: (A) Frequency of TRIZ 40 principles taken from each cell of the TRIZ Contradiction Matrix and (B) the five principles that appear with the highest frequency (C) the five principles that appear with the lowest frequency 45
Figure 14: (A) TRIZ matrix with highlighted portion representing the area of analysis. (B) Frequency of TRIZ 40 principles with respect to the Environmental Engineering Characteristic contradictions. (C) The five principles that appear with the highest frequency... 47
Figure 15: (A) TRIZ matrix with highlighted portion representing the area of analysis. (B) Frequency of TRIZ 40 principles with respect to the Energy Saving Characteristics 19, 20 and 22. (C) The five principles that appear with the highest frequency. 49
Figure 16: Household appliance timeline of product introductions and innovations [35] 52
Figure 17: Distribution of ENERGY STAR-certified dishwasher models sold by a company. Sixteen percent of all ENERGY STAR Dishwashers are sold by Kenmore, 15% Bosch, etc. 'Other' category includes 44 companies that offer less than 30 dishwasher models per company. 56
Figure 18: ENERGY STAR Refrigerators & Freezers Company Distribution 59
Figure 19: ENERGY STAR Clothes Washers Company Distribution............................. 60
Figure 20: ENERGY STAR Room Air Conditioner Company Profile 61
Figure 21: ENERGY STAR Dehumidifier Company Distribution 62
Figure 22: Snapshot of function structure for a clothes washing machine [24] 66
Figure 23: Snapshot of function structure for a clothes drying machine [24] 66
Figure 24: Portion of function structure of clothes dryer [24]... 67
Figure 25: Moisture Settings for clothes dryer [36]... 68
Figure 26: Portion of function model of a clothes washer [24] 69
Figure 27: Method of using an expanded TRIZ database to solve environmental contradictions on the functional level 71
Figure 28: Expanded TRIZ Method Applies in Conceptual Design................................ 71

Figure 29: Comparison of PDP and WBCSD Categories ... 80
Figure 30: Functional model of a household dishwasher [24]. Electrical energy flows and classes are highlighted. ... 82
Figure 31: Functional model of a household clothes washer [24]. Electrical energy flows, signals and classes are highlighted. ... 83
Figure 32: Functional model of a household clothes dryer [24]. Electrical energy flows, signals and classes are highlighted. ... 84
Figure 33: Functional model of a household refrigerator [24]. Electrical energy flows and classes are highlighted. ... 85

List of Abbreviations

DfX – Design for X (X = Assembly, Manufacturing, Environment, etc.)

EBM – Environmentally Benign Manufacturing

EC – Engineer Characteristic

EEC – Environmental Engineering Characteristic

EER – Energy Efficiency Ratio (ENERGY STAR)

EF – Energy Factor (ENERGY STAR)

ENVRIZ – Environmental TRIZ Methodology

LCA – Life Cycle Assessment

MEF – Modified Energy Factor (ENERGY STAR)

PDP – Product Design Process

QFD – Quality Function Deployment

TBL – Triple Bottom Line

TRIZ (TIPS) – Theory of Inventive Problem Solving

UMR – University of Missouri, Rolla

WBCSD – World Business Council for Sustainable Development

WF – Water Factor (ENERGY STAR)

Prelude

If you are an environmental extremist looking for the latest ammunition to protest the unjust actions industry is taking towards Mother Earth, this is not the place for you.

This most recent generation of college graduates grew up under a great deal of environmental pressure. They had different environmental catch phrases written in bold letters around every corner like: 'Save the Rainforest,' 'Save the Whales,' 'Protect the Ozone,' 'Fur is Murder' and 'Always Recycle'. Some teenagers went through the vegetarian rebellion phase to combat cruel animal punishment they saw in movies and on TV. It was a time when the previous generation of Baby Boomers was beginning to realize their impact on the world and the devastation that awaited future generations if actions were not taken.

Fast forward to years later and this young generation is entering adult hood and the working world. They no longer feel as though they have the time and resources to help the environment while some individuals have completely forgotten the message. But "Save the Environment" has been engrained deep in the psyche so that when they throw an empty soda can in the trash there is a moment of guilt and a quick glance to see if there was a recycling bin nearby that would have been a better choice. That is what this research is about, a choice. This is referring to the ability to make the decision to make incremental improvements in the environment. Many of these choices are masked behind a cloak of "this is how we've always done it." This must change. Research and innovations have already brought about alternative environmental choices in design but it has yet to become part of companies' best practices.

1 Introduction

Imagine that you are a socially conscious engineer and you are working on your company's new product line. You recognize the importance of reducing the environmental impact of your product, but you also know that environmental design is done as an afterthought in the current design process. You would like to have a way to be mindful of environmental impact of your design choices in the early stages of concept generation when costs and resources are being committed to a project. But you do not know a way to design for the environment without sacrificing product performance, functionality, time to market, and profit margin. There are perceived contradictions between environmental design and performance targets and profit goals.

TRIZ is a design method that is driven by contradictions that direct the designer to solutions to potentially create an innovative product [1]. TRIZ begins with 39 engineering characteristics that form a matrix of contradictions, for example improving the strength of a metal without making it heavier. Each contradiction is associated with a few of TRIZ's 40 innovative principles, which are derived from the research of millions of patents. TRIZ is a method that provides a link between the contradictions, principles and patents to provide analogous problems with innovative solutions.

TRIZ is a general design tool that is applicable to any product or project so long as a technical contradiction exists in the current best design. Work that has demonstrated the application of TRIZ for environmental design has been attempted and will be discussed. The TRIZ engineering parameters and innovative principles will be analyzed to identify environmental characteristics that are relevant to innovations that decrease environmental impact. This will include a brief description of attempts made to categorize the engineering characteristics into environmental groups. The TRIZ database must be expanded to include products that are environmentally benign so that new products can draw from the environmental innovations. Two product search strategies will be outlined and constrained by a formal definition of a "green" product. The TRIZ database of analogous solutions will be expanded to include products found in the ENERGY STAR database [2]. Function models will be created for the ENERGY STAR products so that a method of searching the database for analogous solutions based on the function models will be given. The work will conclude with an overview of efforts that are underway to further the environmental application of TRIZ.

1.1 Environmental Design Example

Suppose that you are an engineer working for Toyota in the mid 1980's and you drive to work every day in a Toyota Camry that has a 10 gallon gasoline tank. The commute is long and requires frequent stops during the week to refill the gas. You wish to develop a car that will drive further without the need to refill the gas tank. To meet this need, one solution would be to design a car with a 20 gallon gas tank. It will allow you to drive twice as far without needing to refill. However, you recognize that this is not a very innovative design concept, it would not help your market share and it certainly is not an environmental improvement. The other option is to redesign the engine to improve the efficiency of engine, decreasing the amount of fuel needed. This would be a good step forward but how much additional mileage would this actually produce? An innovative solution to this problem of driving further on a tank of gas may exist but is not apparent for this application and so TRIZ will be used to generate concepts to overcome this contradiction.

The basic contradiction you experience is between engineering characteristic 19: Energy Consumption by a Mobile Object and EC 31: Harmful Effects Caused by Object. You look up the contradiction in the TRIZ matrix finding the innovative principle 28: Replacement of Mechanical System. Within that principle will be solutions to designs achieved by overcoming the same contradiction, including a design that substituted an electric engine for a gas engine (this could be a lawn mower, train, etc.) This would lead the design team to pursue an innovation that will become a hybrid engine that will give you more gas mileage out of your current 10 gallon tank and reduce harmful effects on the environment.

This is a simplified and obvious example of environmental use of TRIZ. Increasing the size of the gas tank solves the problem statement but has no mechanical advantage and reduces performance through the additional weight. TRIZ provides innovative examples in which ideas were applied to include environmentally benign products and searching the database through function structures will provide a greater chance for environmental improvements. However, there is no intention that the examples will overcome the contradiction in an environmentally benign way.

1.2 First Generation Environmental Design Strategies

The obvious environmental improvements to a product include replacing harmful material, reducing product wastes and reducing manufacturing wastes. These strategies are considered the quickest environmental fixes. Material replacement and reducing wastes are the “low hanging fruit” of environmental initiatives. There is a clear and immediate understanding of the value and provide the biggest most marketable environmental impact. An example would be the recent legislation that required electronics to use lead-free solder. Solder that does not contain lead has performance drawbacks and dirtier manufacturing processes but it is a step towards environmental improvement. More innovations are necessary for lead-free solder to reach the performance measures of leaded solder. Continuous environmental improvements are made in smaller steps and require constant product revisions and upgrades [3-9].

1.3 Next Generation Environmental Design Strategies

In contrast to the first generation strategies, the goal of the next generation of environmental design is to assimilate the DfE mentality into the beginning of the product development process so that it will have an effect beginning with the conceptual design phase. One approach in the next generation is to target specific products to improve performance towards environmental goals. This may mean improving products that are not explicitly harmful but have opportunities to minimize environmental impact. There are government and private organizations such as the World Business Council for Sustainable Development (WBCSD) (see Chapter 2.2) and ENERGY STAR (see Chapter 6) that are identifying metrics to assess the environmental impact of products.

A second approach to the next generation of environmental design is to make it part of the standard design practices for a company. This is best accomplished by modifying design methodologies to integrate DfE guidelines into the practices so that it becomes second nature to designers much like what has happened with DfA and DfM heuristics. Integration of DfA and DfM was driven by the cost savings they provide. It was also easy to incorporate manufacturing engineers into product development teams. Statistical quality control (SQC) is an example of a method for improving products where the cost savings were not immediately apparent. It required corporate commitment for success. Now, SQC is standard practice and the advantages to the company are well established.

Environmental design is in the early adoption stage. In contrast to SQC, DfA and DfM, it is not explicitly driven by cost savings. Most interventions in design due to environmental considerations are driven by legislation and corporate policy. Environmental gains in products often occur in downstream life cycle impacts, which are not obvious to the bottom line. To make matters worse, environmental engineers are not as common in corporations as quality and manufacturing engineers, so there are fewer champions of environmental goals. It is challenging to find and include an engineer who is also an environmental champion into design teams.

This work uses TRIZ as the methodology to be used to infuse DfE in an integrated fashion into the conceptual design process. The environmental expansion of TRIZ will strengthen its use in all design situations. The motivation of selecting TRIZ is discussed in more detail in Chapter 2.5.

1.4 Research Questions

The fundamental research question for the basis of this work is: Can the TRIZ method be expanded to help design teams that place a high value on environmentally benign designs? This can be broken down into more specific questions. Question One: How would one find products to expand the TRIZ database specifically so that it can be more useful for environmentally benign design changes? Question Two: How can function structures be used to catalog environmental innovations and aid in applying TRIZ principles? This work will demonstrate how this expansion of TRIZ can be accomplished and will yield three unique contributions.

1.5 Organization of Thesis

This thesis begins with Chapter 2, a background review of current industry trends towards improved environmental design, an overview of the product design process, function models, specific design for environment methodologies and the TRIZ concept generation method. Chapter 3 will outline the definition of an environmentally benign product (green product) and propose two search strategies for locating products to be included in the existing TRIZ database. Chapters 4 and 5 will describe the TRIZ 39 engineering characteristics and 40 innovative principles in detail. It will use the existing matrix to narrow the search fields to a manageable domain so that an environmental product base can be constructed. This will give way to a discussion in Chapter 6 on the ENERGY STAR database as the primary source for products that overcome an energy contradiction. ENERGY STAR metrics, specifications and product information will be presented. Finally, Chapter 7 will outline the method of using function models as an identification and product comparison technique.

2 Background

This chapter will provide a review of the literature as it relates to industry trends, the product design process, function models, design for environment methods, the TRIZ methodology and work that has been done to relate TRIZ to environmental design.

2.1 Product Design Process

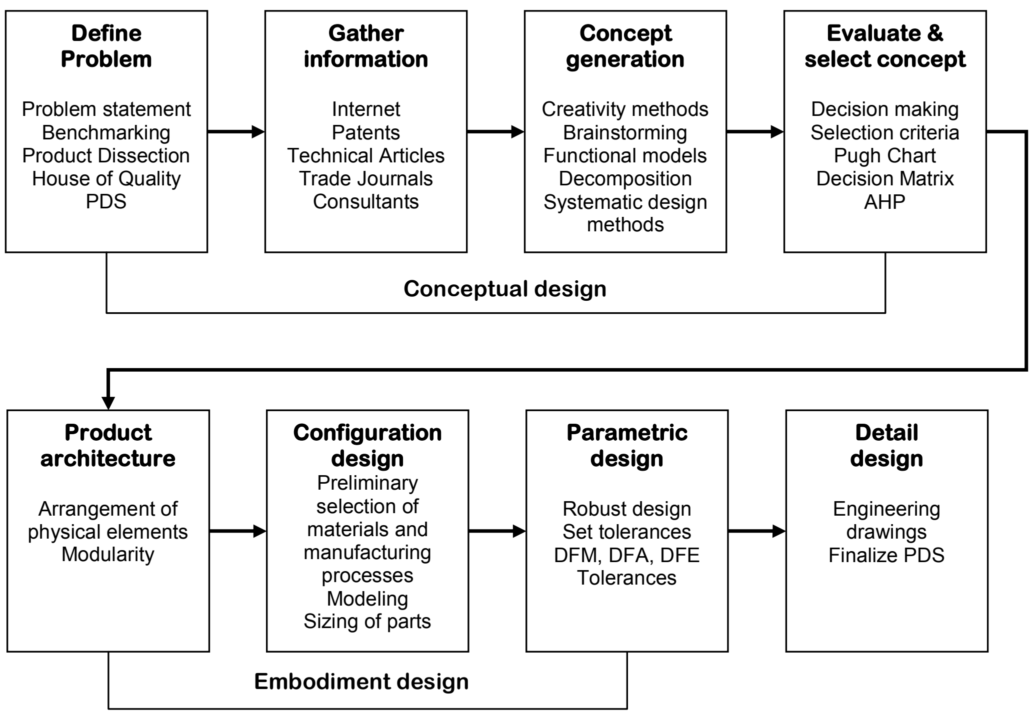


Figure 1: Schematic of Product Development Process [4]

Dieter developed a process flow chart describing the process used in engineering to create a product, Figure 1 [4]. The Product Development Process (PDP) is a detailed description that begins with a problem definition and continues through what Dieter has defined as conceptual embodiment and detail design phases. Conceptual design consists of information gathering such as literature reviews, patent searches, market analysis and customer responses. This information feeds into the Quality Function Deployment (QFD) tools that help translate customer requirements into engineering characteristics. These characteristics are then used to make informed comparisons between concepts. The embodiment design phase begins when a single concept has been chosen and detailed design begins. The product begins to take form during the product architecture and configuration design stages. The design team creates a preliminary layout of the product, material selection, manufacturing processes and dimensions. One part of parametric design applies Design for X (DfX) tools to refine the choices made in the previous steps. Tools that have become standard practice in this step include Design for Assembly (DfA) and Design for Manufacturing (DfM). The final step in the PDP is to create detailed drawings of the product that include all dimensions and manufacturing process. These drawings should be as complete as possible because they are sent to suppliers to get quotes and create subcomponents and tooling [10, 11].

Tools such as Design for Assembly and Manufacturing were once demanded as a step in the design process. They included steps to reduce costs and increase productivity. Examples of the guidelines for DfA are minimizing the total number of parts, minimize the assembly surfaces, and avoid separate fasteners. DfA and DfM are explicitly applied in the parametric design phase but have become part of general design knowledge and therefore are considered much earlier in the process during conceptual design. Design for the Environment (DfE) is included in parametric design as a DfX. It follows that DfE will become part of good engineering practices as awareness increases.

The most common perception of environmental design is material replacement. Sridhar proposes methods to include environmental strategies into the material selection process [9]. There has been work done on other DfX processes that are part of environmental design. Dhillon has created mathematical models that can be applied to designing for reliability of systems [3]. Okogbaa has made similar strides in designing for maintainability [8]. Reliability and maintainability address issues important to environmental design and so are important considerations in DfE. These authors agree that formally developing these DfX techniques are important to the integration and understanding of best environmental design practices.

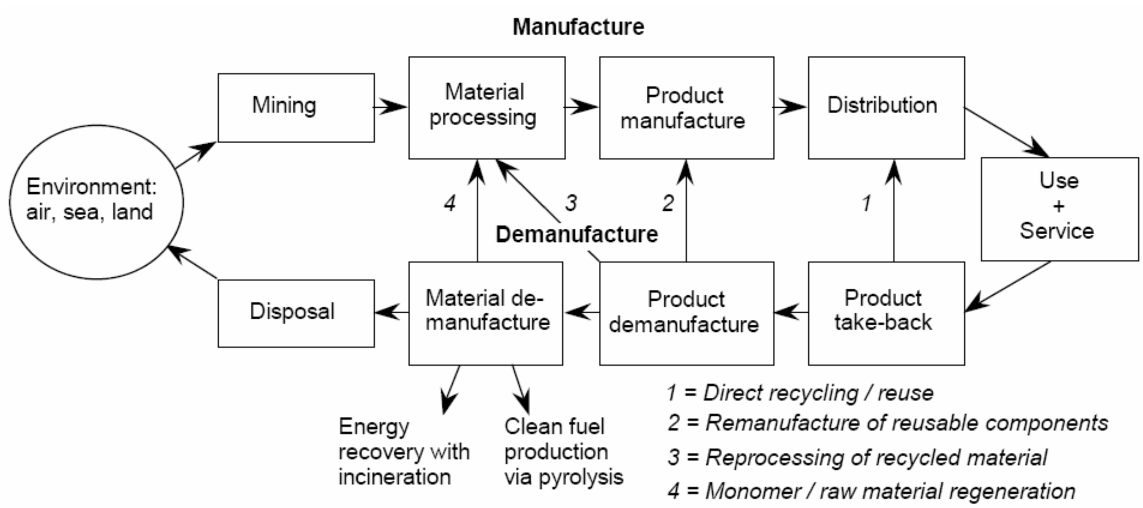


Figure 2: Generic representation of a product's Life-Cycle from cradle to grave and reincarnation [12]

Bras injected a different point of view on DfE into the PDP [12]. The decisions made in the PDP shown in Figure 1 influence different material life cycles as depicted in Figure 2. A material life cycle is a representation of each process step that a material will experience beginning with extraction from the environment through useable life and ultimately disposal. DfE (including aforementioned design for reliability and design for maintainability) is a strategy to consider the longer effects of the product during use.

Tools such as the Life Cycle Assessment (LCA) and Eco-Compass can be used to measure the impact of different design choices. These concepts will be described in more detail in the next section [12-14].

2.2 Design for Environment

Design for Environment (DfE) is used to describe design decisions that influence the environmental impact of a product. DfE is defined as “the systematic consideration of design performance with respect to environmental, health, and safety objectives over the full product and process life cycle”[5, 15-17]. It can be broken down into more detailed DfXs such as material recovery, disassembly, reliability, and waste recovery [4]. McDonough etal. outline five steps to eco-effectiveness in companies [14]:

1. Get “free of” known culprits;
2. Follow informed personal preferences;
3. Creating a “passive positive” list – organizing materials and processes into categories of environmental harm;
4. Activate the positive list – implementing items in step 3 that are actively defined as environmentally healthy;
5. Reinvent.

McDonough’s book Cradle to Cradle is an environmental innovation in itself. Chapter 1 is entitled “This book is not a tree” and describes how the book is printed on entirely synthetic paper that does not involve trees and uses a cleaner manufacturing process than traditional paper. The realization of the need to consider the entire life of a product from creation to disposal (cradle to grave) is a common theme in any literature work on environmental design. Some design methods have been developed to aid in this consideration, like Life Cycle Assessment (LCA) which is a method of identifying environmental opportunities in product design [12, 13].

The LCA methodology identifies energy and materials used and the wastes created by a product or process. LCA is applied to the entire life cycle of the system from raw materials to disposal. It forces a company to take responsibility for more than the creation and sale of the product. The LCA process has been adopted by major companies including Toyota, 3M, AT&T, ExxonMobil and research at universities including Carnegie Mellon, MIT, and Princeton. A way to perform a life cycle assessment of a product is to use the eco-compass.

Fussler & James developed an eco-compass in 1996 that condensed business and product development into a simple graphical model that could be easily read, Figure 3 [13]. The eco-compass is based on six categories that are defined in detail by Jones & Harrison:

- Mass Intensity
- Energy Intensity
- Extending service and function
- Health and environmental risks
- Resource conservation
- Reuse & revalorization of wastes

The eco-compass provides a way to compare a base product case to a new option. The purpose is to evaluation the current situation or product on an integer scale of 1 through 5 with respect to the environmental issues listed above. Then the new product, process or plan is evaluated in each category and given a separate rating. These ratings are compared on a plot to quickly view the environmental benefits of the new option. An example of an eco-compass developed for an existing and proposed product is given in Figure 3. The eco-compass can be used as a benchmarking tool to determine areas of environmental improvement for one product compared to other products. Categories that rank low can be decomposed to determine performance contradictions that can be fed into the TRIZ methodology to generate new concepts. Eco-compass could also be used as a decision making tool for concept selection. It could be a way to visualize the environmental impact of different concepts.

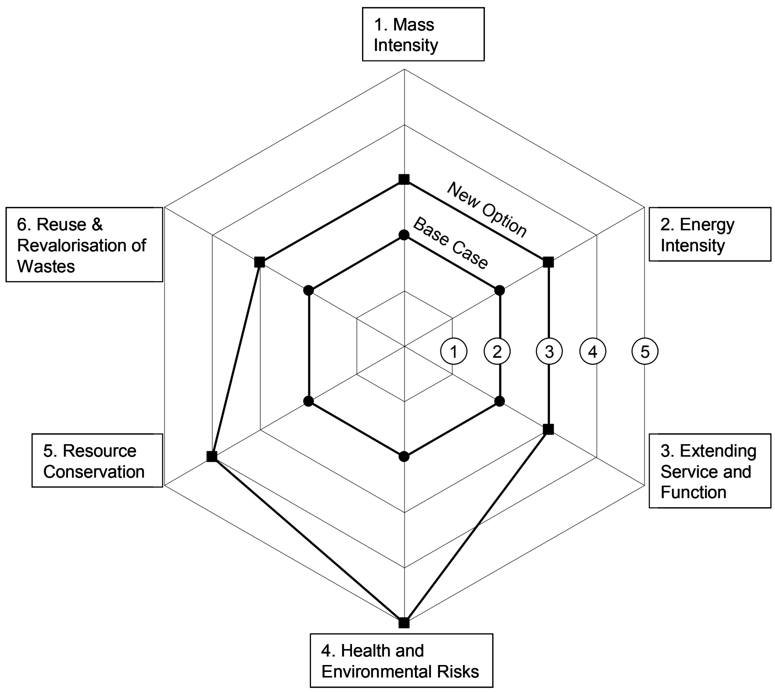


Figure 3: Example of Eco-Compass[13]

The World Business Council for Sustainable Development (WBCSD) has made further efforts to categorize environmental impact [18, 19]. The WBCSD was established in 1992 and is a CEO-led global association consisting of over 190 companies from 35 countries in 20 industrial sectors. The WBCSD Website at www.wbcsd.org describes three key areas of environmental focus: Energy and Climate, Development and The Business Role. The WBCSD is more applicable to the corporate structure and business plan development of environmental design. The goal is to create and implement business practices that will minimize the stress on the environment. Although the WBCSD approaches the problem at a corporate level, the ideals will filter down as engineering specifications and constraints. For this reason, the efforts by the WBCSD are valid for discussion in product environmental design. The WBCSD created seven categories of interest in creating environmentally benign products:

- Reduce the material intensity of its goods and services,
- Reduce the energy intensity of its goods and services,
- Reduce the dispersion of any toxic materials,
- Enhance the recyclability of its materials,
- Extend the durability of its products,
- Increase the service intensity of its goods and services.

The WBCSD and eco-compass categories are similar and are compared in Figure 4. The WBCSD categories of Durability and Service Intensity can be combined into the Eco-Compass category of Extending Service. Thus, there is a direct relationship between each of the categories while Liu and Chen use the WBCSD categories to group the TRIZ engineering characteristics, which will be discussed in Chapter 2.5 [19].

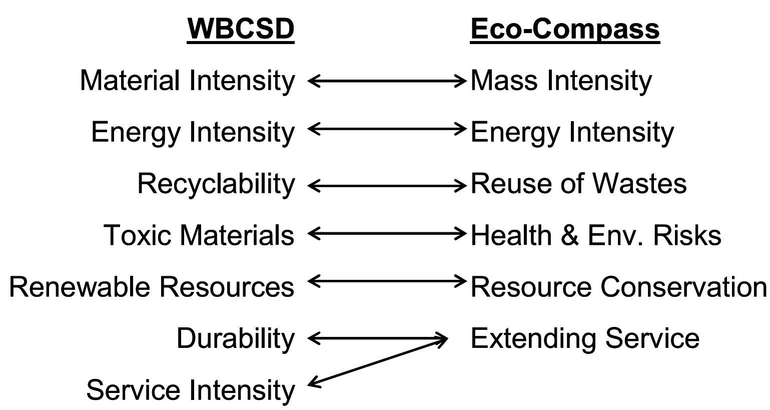


Figure 4: Environmental Category Comparison of WBCSD and Eco-Compass

2.3 Functional Models

Engineers, by nature, decompose a product into the most basic systems and functions. Function modeling is a visual way to represent a product or system at an abstract, solution neutral level. There are considerable efforts under way at the University of

Missouri, Rolla to create a repository of function models using a unified language approach known as functional basis. The functional basis a unified, finite language from which all function models can be created.

The concept of function structures is inspired by a process developed by General Electric in the 1940s called Value Engineering [20-24]. Value Engineering was a cost model that assigned cost values to different functions of a product to identify high-cost areas and reduce manufacturing costs. During this same time, Altshuller was constructing the 39 engineering parameters that could be considered an attempt at abstracting innovative products to a functional level. Pahl and Beitz made the first attempt at constructing a unified functional language in 1984 by introducing five higher level functions and six higher level flows [25]. Since then, researchers have developed a more thorough set of functional terms [24]. The functional classes and flows are listed in three levels to allow freedom to express a product in abstract ways, Table 1 and Table 2. This also provides a stopping point for the level of detail that is put into a function structure.

Table 1: Example of primary and secondary functional classes [24]

Class	Basic	Class	Basic	Class	Basic
	Separate		Actuate		Sense
Branch	Distribute	Control	Regulate	Signal	Indicate
	Import	Magnitude	Change		Process
	Export		Stop		Stabilize
Channel	Transfer	Convert	Convert	Support	Secure
	Guide		Store		Position
Connect	Couple	Provision	Supply		
	Mix				

Table 2: Example of primary and secondary functional flows [24]

Class	Basic	Class	Basic	
	Human		Human	Mechanical
	Gas		Acoustic	Pneumatic
Material	Liquid		Biological	Radioactive/Nuclear
	Solid	Energy	Chemical	Thermal
	Plasma		Electrical	
	Mixture		Eletctromagnetic	
Signal	Status		Hydraulic	
	Control		Magnetic	

A function model can be created from a product once the class and flow terms are identified. A function model begins with a black box approach to a problem highlighting the flows entering a system and the flows exiting the system. A black box for a standard portable household heater is shown at the top of Figure 5. For a room heater, the input flows are gas, electrical energy and an ON/OFF signal. The flows exiting the black box are hot gas, thermal energy, rotational energy and the signal. Figure 5 shows the function structure of a room heater including the classes and flows from the functional basis language. Bohm and Stone have published work building from the UMR design repository that show how function structures can be used as search criteria for databases and also as concept generation tools [20]. Their concept generation technique, like TRIZ, is a type of design by analogy. Products can be abstracted into function structures and compared to identify portions of the function structure that are similar, indicating that the physical solutions may applicable. Chapter 7 will discuss the rationale for using function models to search the TRIZ repository and provide examples of design improvements through function flow sets.

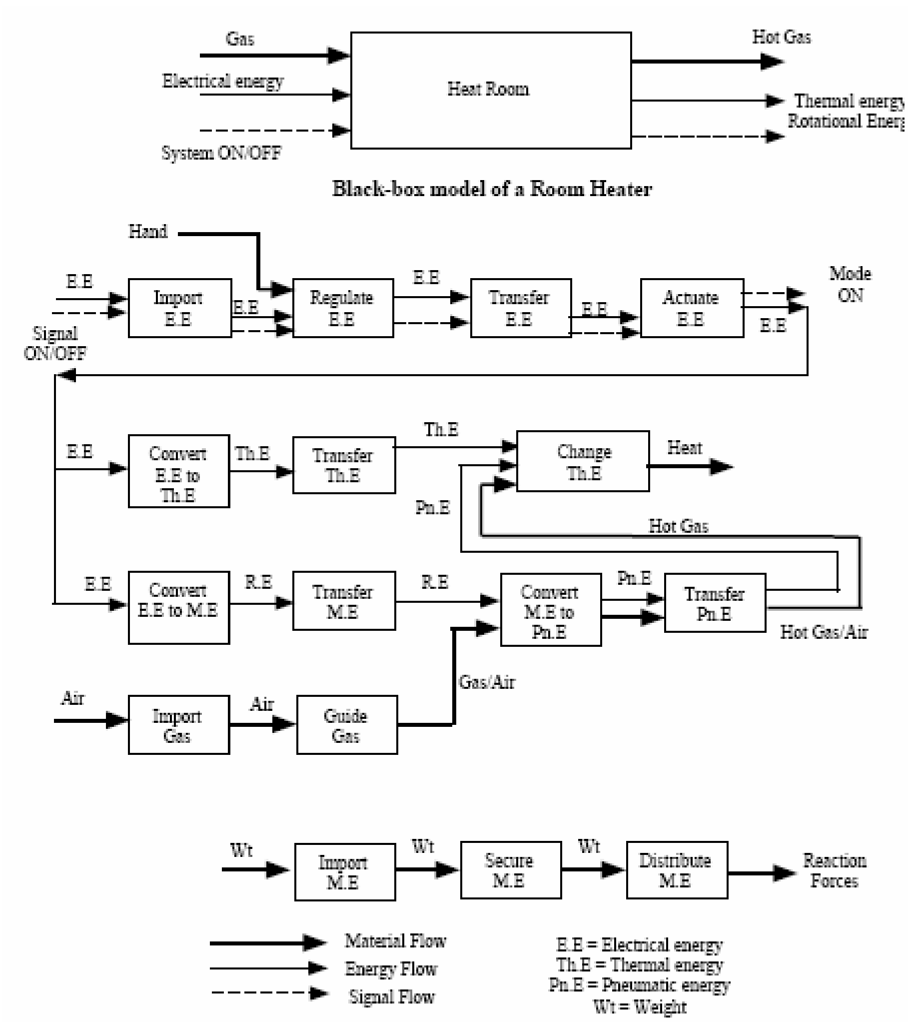


Figure 5: Function model of household portable room heater [24]

2.4 TRIZ

TRIZ is an acronym for the Russian phrase *Teoriya Resheniya Izobretatelskikh Zadatch* which stands for the Theory of Inventive Problem Solving (TIPS) [1]. TRIZ was developed in the 1950s and 1960s by a Russian patent examiner named Genrich

Altshuller. The first literature about TRIZ was published in 1973 by Altshuller entitled The Innovation Algorithm. During Altshuller's time, invention was thought to be a random act and that some people were more prone to develop new ideas than others. It was Altshuller's belief that there could be a systematic approach to invention. He and his team spent years searching and analyzing over 1 million patents to discover that a majority of the engineering problems that were being faced had already been solved. The power of TRIZ has been that it is based directly upon patents. Because patents are innovative by definition, a design method rooted in patent research would yield innovative solutions.

Altshuller built a foundation for innovating products, Table 3 [1, 16]. He found that patents could be subdivided into different levels of innovation. Level 1 is an apparent solution that is based on personal knowledge. Level 5 is a discovery that is unknown to all in any industry. He went on to create the Law of Ideality that asserts that the best system is one that operates on its own. For example, the best container is no container. The Law of Ideality is an interesting approach to solving problems because it forces the designer to consider what it would take to create a solution by adding nothing extra. This becomes an interesting question when dealing with environmental design because the reduction of material and energy is a fundamental to becoming environmentally benign.

Altshuller also developed patterns of evolution, shown in

Table 4, which can be used to predict the next level of innovation in an industry or product family. These patterns can help a designer anticipate the next step in the product evolution. Altshuller stated that innovations exist to overcome contradictions. The example given is that an increase in the strength of a metal plate also increases the weight. In many engineering design applications this change would increase one objective (strength) while producing an unwanted performance (increased weight). Overcoming this contradiction will produce a new innovation.

TRIZ provides a contradiction matrix that organizes the technical contradictions into pairs represented by the intersection of the columns and rows. TRIZ inventive principles that could be used to overcome the contradictions were placed in the proper intersecting cells. A more detailed description of the contradiction matrix and associated innovative principles will be given in Chapter 4 and 5.

In many ways, Altshuller's work paralleled work to create a unified language of function structures. Whereas the function basis decomposes a system into fundamental functions and flows, TRIZ abstracts a problem into technical contradictions between engineering parameters. The TRIZ and function structure concept generation methods are similar because they each use an abstracted view of a problem to find analogous solutions. Chapter 7 describes how function models can be used in TRIZ.

Table 3: Foundations of TRIZ [16]

Foundation	**Description**	**Further Explanation or Example**
Technical Systems	A technical system is anything that performs a function. The most simple technical system consists of two elements with energy passing from one element to the other. Any technical system can have one or more subsystems.	**Technical System 1**: Chalkboard (Chalk + Blackboard + Applied Force) **Technical System 2**: Chalk (multiple elements + chemical bond)
Levels of Innovation	Altshuller proposed that all inventions are not equal in inventive value. The example column describes the five levels of innovation. The first statement after the level indication is the degree of inventiveness and the statement after the semicolon is the required source of knowledge. While utilizing TRIZ can assist a designer with problems in Levels 1-4, it is most practically used in solving Level 3 and Level 4 problems.	**Level 1**: Apparent Solution; personal knowledge **Level 2**: Minor Improvement; knowledge within company **Level 3**: Major Improvement; knowledge within the industry **Level 4**: New concept; knowledge outside the industry **Level 5**: Discovery; all that is knowable
The Law of Ideality	The Law of Ideality states that any technical system, throughout its lifetime, tends to become more reliable, simple, effective – more ideal. When a system reaches ideality, the function is performed without the system.	Instead of using wasting cargo weight using refrigerated cargo planes to transfer meat, fly the plane at a higher altitude where the atmosphere will keep the meat inside cold.
Contradictions	A contradiction occurs when the improvement on one parameter of a technical system results in the deterioration of another parameter of a technical system.	Increasing the strength of a metal plate increases its weight.
Patterns of Evolution	Technical systems follow eight patterns of evolution	Products are redesigned to become more effective and efficient over time

Table 4: TRIZ patterns of Evolution [16]

Pattern of Evolution	Further Explanation or Examples
Life Cycle	Technology follows a life cycle of birth, growth, maturity, decline.
Dynamization	Automobiles controlled by engine speed, then gearbox, then automatic transmission, then continuously variable transmissions.
Multiplication Cycle	Boom boxes evolved from adding separate components (stereo, cassette player, CD player) together.
Transition from macro to micro level using energy fields to achieve better performance or control	Wood burning stoves to gas ranges to electrical ranges to microwaves.
Synchronization	Primitive subsystems hold back development of total system.
Scaling up or down	Old computers weighed several tons and had less computing power than laptops today.
Uneven development of parts	Assemblies are originally made from uncoordinated parts, followed by integrated designs, culminated by parts whose characteristics are changeable upon demand. An example would be car brakes.
Replacement of human	Washboard to automatic washing machine to automatic washing machine with automatic detergent dispenser

2.5 Environmental TRIZ

The design literature includes work done to improve the TRIZ methodology for use in environmental design. Liu and Chen grouped the 39 TRIZ ECs based on the WBCSD categories [18, 19, 26]. Table 5 summarizes the results from their work. Liu and Chen asserted that any of the 39 ECs could be used to form an environmental improvement in some design scenario. The categories from WBCSD are based on the properties of a product For example, service intensity describes the amount of work needed to maintain a product during the life cycle. In contrast, categories presented in this work will organize the ECs with respect to the product development process, as shown in Appendix

B. Liu and Chen did not provide guidelines for how to use these environmental groups when applying TRIZ to create environmental innovations.

Chang and Chen provided examples of an environmentally benign example for each of the 40 TRIZ principles [27]. Notable innovations described in their work include stacked dies for the TRIZ principle Nesting, the Forever Flashlight for Prior Action, and automatic faucets for Self-Service. Their work demonstrates that each TRIZ principle can be illustrated by an environmental innovation. Chang and Chen provide single example for each principle, but more examples and information are required for individual principles for the TRIZ method to be fully utilized.

Researchers are continuously trying to provide examples to validate TRIZ as an environmental design methodology. The information given in Table 5 could be used to narrow the list of ECs and help a designer form the technical contradictions. For example, if a critical part of the design is improving durability, then according to Table 5 the designer should begin with ECs 13-16, 30 and 34 to form technical contradictions. Liu, Chang and Chen are finding environmental examples of the TRIZ principles whereas this thesis is finding environmental examples that overcome TRIZ contradictions. Their examples are independent of a specific technical contradiction while this research provides examples that are initiated with a specific technical contradiction.

Table 5: Relationship of TRIZ ECs with World Business Council for Sustainable Development eco-efficiency categories [19, 26]

		Material Intensity	Energy Intensity	Toxic Material	Recyclability	Renewable Resources	Durability	Service Intensity
1	Weight of Mobile Object	x	x					
2	Weight of Stationary Object	x						
3	Length of Mobile Object	x	x					
4	Length of Stationary Object	x						
5	Area of Mobile Object	x	x					
6	Area of Stationary Object	x						
7	Volume of Mobile Object	x	x					
8	Volume of Stationary Object	x						
9	Rate of Change, Speed				x			x
10	Force Exerted by Object				x			
11	Stress, Pressure Exerted upon Object				x			
12	Shape of Object	x						
13	Stability of Object's Composition			x			x	
14	Strength of Object	x				x	x	
15	Durability of moving object						x	
16	Durability of non-moving object						x	
17	Temperature		x					
18	Brightness		x					
19	Energy spent by moving object		x					
20	Energy spent by non-moving object		x					
21	Power		x					
22	Waste of energy		x					
23	Waste of substance	x						
24	Loss of information							x
25	Waste of time							x
26	Amount of substance	x						
27	Reliability							x
28	Accuracy of measurement				x			
29	Accuracy of manufacturing				x			
30	Harmful factors acting on object					x	x	
31	Harmful side effects			x				
32	Manufacturability	x	x		x			
33	Convenience of use							x
34	Repairability					x	x	
35	Adaptability							x
36	Complexity of device				x			
37	Complexity of control							x
38	Level of automation							x
39	Productivity	x	x					x

2.6 Industry Trends

Trends that eventually become a standard practice within an industry begin with early adopters. Trends can be influenced by the internal motivations of a corporation, competition, legislation or industry changes. Early adopters tend to be organizations that are financially successful and can afford to invest in new concepts. These larger companies have the time and resources to apply new ideas on a large scale and observe the effects. Small companies are more focused on being quick to the market and financial status. Trends occur when an idea is successful in an early adopter and filters to the rest of industry. Examples of design and manufacturing trends that have become standard practice in industry are automation, quality control, and, most recently, environmental awareness [4, 10, 12, 13, 28].

Allen et al. studied trends in environmentally benign manufacturing (EBM) from the world leaders in manufacturing, Europe, Japan and USA [29]. This work was funded by the National Science Foundation in cooperation with the Department of Energy conducted through the World Technology Evaluation Consortium. The year long study showed that European and Japanese governments are more pro-active in creating cooperative efforts with industry to create environmental legislation. The governmental foundations are also more business driven and thus incorporate environmental design strategies into business strategies. In contrast, US industry is more material and process focused, leading the government to produce laws that require "point solutions" instead of system solutions. As the US government begins to take a more active roll in environmental legislation, corporations that have an environmental design process in place will make the adjustment easier. Bras supports these findings and asserts that larger corporations are adopting internal environmental policies [12]. Bras provides more detailed examples of corporate structures and hurdles to implementing an environmental mentality from the top-down.

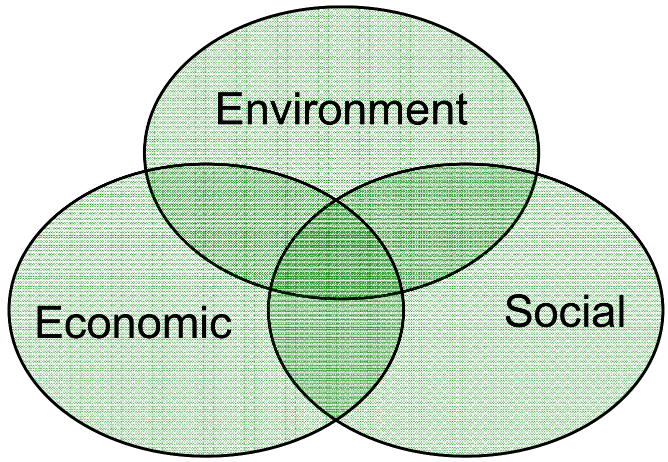


Figure 6: Triple Bottom Line

The triple bottom line (TBL) is a corporate strategy with the goal to create a balance between environmental quality, social improvement and economic prosperity [30, 31]. Each of these categories can be considered individually, but the triple bottom line reflects the belief that a long sustaining organization must achieve a balance of the three to flourish, Figure 6. The triple bottom line brings proactive environmental structure and improvement to the foreground of the business strategy and treats it as a necessary step to the survival of a product and corporation. A process that is often used in corporations that adopt the TBL is Life Cycle Assessment (LCA). Good environmental practices are in the process of being adopted by companies and industries. Quality control techniques are an example of trends that have recently evolved into standard practices and draw many similarities with environmental design [32].

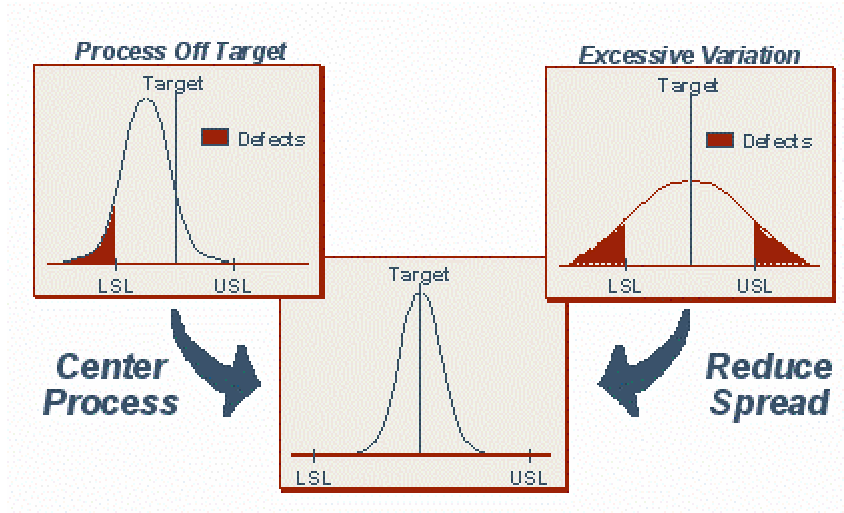


Figure 7: Examples of Six-Sigma variation plots showing an off target process (upper left), wide variation from target (upper right) and the ideal scenario (bottom middle) [33].

For decades after the industrial revolution in the United States the label "Made in USA" was a stamp of quality. Japanese made products had a stigma of lower quality, lower cost goods. In the mid 1980s Six-Sigma was developed by Motorola Corporation to understand and control the variation of manufactured products and reduce the number of defects. Six-Sigma, by statistical definition, is reducing the number of defects to 3.4 per million opportunities. Six-Sigma analyzes the current manufacturing processes to produce process control plots such as those in Figure 7. The top left shows a process that is off of the design target, meaning that the statistical mean of the process is not equal to the required mean of the design. The top right plot is an example of a process with excessive variation, meaning that the process is producing items with a very large range of measurements and produces products that do not fit the designated tolerances. The highlighted areas of these two plots represent items that would be rejected as defective by the quality standards. The lower middle plot would be representative of a process that is controlled and within specifications. It is nearly impossible to have a process with zero variation and so the goal is to reduce the amount of variation. Six-sigma provides a method to improve manufacturing processes called DMAIC: Define, Measure, Analyze, Improve and Control. In the early 1990s, Japanese organizations began to adopt the six-sigma methodology and other quality control processes and initiated a paradigm shift towards reducing variation and defects, thus improving quality and reducing costs. Through adopting these methodologies, Japanese made products and electronics are now considered the leading edge of innovation [34].

Improving quality decreases defects and ultimately saves money, however there exists a balance between the money spent to improve quality and the number of additional defects the improvements will save. Eventually, the money saved in reducing defects can outweigh the money spent in improving quality. To this day, six-sigma is continuously being adopted by more organizations as the need for improved quality becomes a larger factor in the marketplace. The advantages of implementing quality control techniques were not immediately obvious and so it took early adopters to prove worth. Designing for quality control eventually became integrated into the traditional design process. Quality is now expected in products and the consumers are willing to pay extra for what is considered 'good quality' goods. Environmental design is now an explicit step in most design processes but should become a seamless step. Eventually, the same good practices and conceptions that now motivate and reward quality will also surround the environmentally benign aspects of products. The work that is being done now to further environmental design is vital for this integration.

3 Creating a Method for the TRIZ Database Expansion

The TRIZ database is populated by products and patents that overcome engineering contradictions in an innovative manner. This research will expand the TRIZ database to include environmentally benign innovations. Expanding the TRIZ database for environmentally benign innovations will not succeed by only examining patents because the environmental innovations are not necessarily patentable as will be shown by the definition of green. For example, increasing energy efficiency is most often beneficial for the environment but may be done in a technically obvious way. Obviousness makes it not able to be patented.

Describing the methodology used to find the right products to include in the TRIZ database begins with a discussion of the formal definition of a green product. This definition will feed into two separate search strategies for finding environmental products to be included into the TRIZ database. The first search strategy is a random product search and the second strategy is a search in the existing TRIZ database. What is used is a hybrid of the two strategies. Finally, a method of using the environmental aspects of the TRIZ database will be discussed.

3.1 Definition of "Green" Products

The terms "environmentally benign", "environmentally friendly" and "green" will be used interchangeably within this work. For a product to be considered green, it must be considered more environmentally friendly than its predecessor products while maintaining or improving functionality and performance. This work will focus on

ENERGY STAR products since they reduce the amount of electrical energy consumed while improving functionality. The reasons for choosing ENERGY STAR are explained in Chapter 4.

The reduction of electrical energy may not be as obvious a green innovation compared to emissions, fuel or waste, but it is equally important. The amount of energy saved in a single product may not appear significant but when thousands of consumer products taken into account, the savings become considerable. Recall the goal of this work is to develop the next generation strategy.

> *A green product is a system that includes an innovative design that allows it to be more environmentally benign than its predecessor products.*

3.2 Search Strategy Proposal One: Product Search

To select members for a database of environmentally friendly products, one strategy would entail searching for all possible green products in the world to include in the database. Methods that could be used to locate products include literature searches, Internet searches, company contacts, catalog searches, and patent databases. This would provide the database with a diverse set of products. This set of search tasks is encompassing but unrefined and cannot be used explicitly as the primary strategy to develop an initial database. Once a database of environmentally friendly products is established in TRIZ, any method could be used as new products are discovered. Figure 8 outlines a structured strategy that could be used to catalog any green product from any industry. Each step in the process is numbered from 1 through 7 with the final goal of creating an expanded TRIZ database that contains environmentally friendly products and the associated functional models.

Referring to the numbered references in Figure 8, the search begins with a need (1), find a method of locating and recording green products. The need flows into the definition of a green product (2), which acts as a constraint on the search. Therefore, the product must be more environmentally benign than its predecessor, a mechanical product, and overcome a design contradiction. Once the product is found (3) it is abstracted to a functional level (4), which will neutralize any preconceptions of the system and provide a way to find applicable analogous solutions in the database. The reasons for using functional models will be discussed in Chapter 7. The function groups that relate to the environmental improvement are highlighted (5) and examined to determine the contradiction between the performance measure and environmental impact (6). This analysis may yield multiple combinations of engineering characteristics in order to accurately describe the innovation. This occurs when the contradiction is not as obvious and multiple routes must be examined to determine the best possible application(s) of TRIZ. The various contradictions will produce multiple TRIZ principles (7).

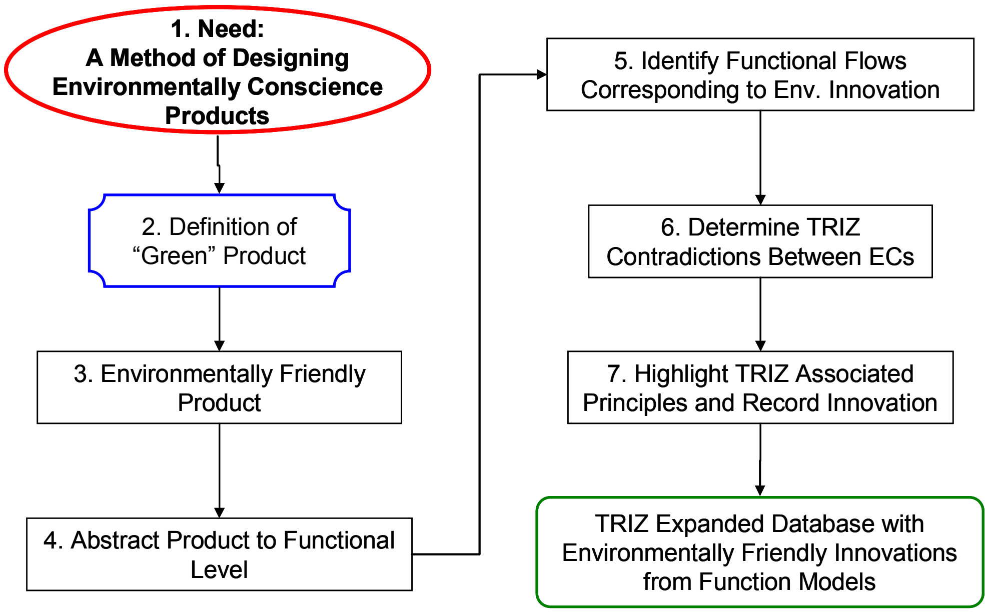


Figure 8: Search Strategy Proposal One: Environmental Product Search

3.3 Search Strategy 2: Analyzing the Existing TRIZ Database

Searching for individual products that exist in industry can be a tedious, never-ending task. The TRIZ database already contains a large number of patents, products and information that is organized by innovative principles. TRIZ is not, however, organized for searching within the database, nor does it have products abstracted to a functional level. TRIZ examples are organized by the TRIZ principles and may not be relevant for the technical contradiction under consideration in a DfE scenario. The TRIZ method, as it is now, assumes that any effort at environmental improvement is made as the initial intention and thus will be “handled” in the selection of ECs and contradictions. However, this assumption may not always be accurate. This section discusses a second search strategy that analyzes the existing TRIZ database to find and abstract environmental innovations to the functional level. This search strategy is outlined in Figure 9.

Search strategy 2 begins with the same need statement (1) as search strategy 1: locate and record green products. The next step in the process is to decompose the existing TRIZ engineering characteristics to determine which ones are more associated with environmental improvement to create Environmental Engineering Characteristics (EEC) (2). A more detailed discussion of EECs will be given in Chapter 4. The contradiction set of the EECs will lead into the set of 40 innovative principles (3). One strategy for searching the principle database would be to start with the principles that have the highest frequency of appearance. It will be shown that the principles do not appear with the same frequency throughout the matrix. Each principle contains a set of solutions that have applied that innovative concept to overcome a contradiction (4). Products and patents from this solution space can be identified through applying the constraint that it must be a green product (5). The environmental innovations found within each principle form a subset of solutions within the existing database (8). Like search strategy 1, functional models can be built from this subset of products in order to facilitate the search of the database (6). The functional flow sets that correspond to the environmental innovation are highlighted (7). These functional models then lead back into the environmental solution space of the existing database (8).

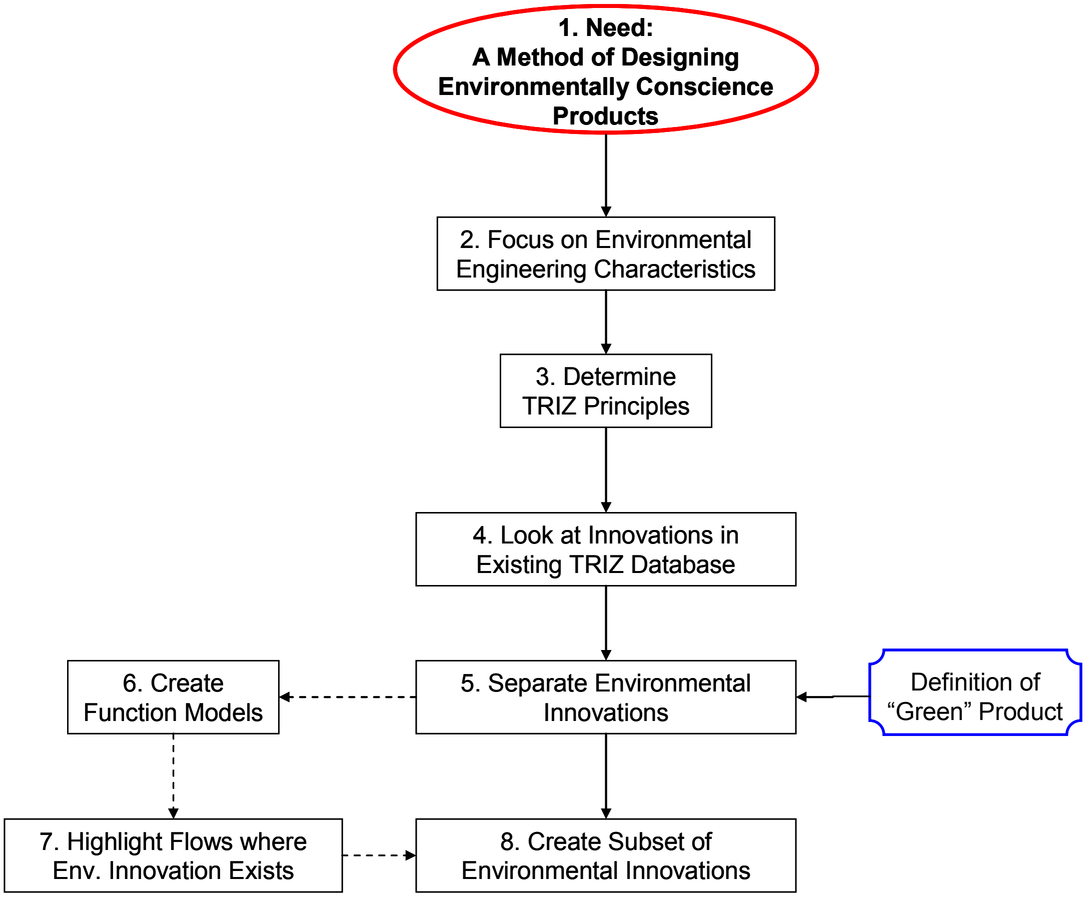


Figure 9: Search Strategy Proposal Two: Searching Existing TRIZ database for Environmental Innovations

3.4 The Application of Search Strategies

These two search strategies reflect the main processes that are used to demonstrate the use of TRIZ as an environmental concept generation tool. Each strategy has inherent advantages and disadvantages. The first strategy, finding new products, could provide a large breadth of the solutions to be added to the existing TRIZ database. The power of analogy is as strong as the solution space it contains, so any addition to the database increases the usefulness of TRIZ. However, there are far too many products existing in the global market to conduct random searches. Therefore, the search must be focused in a direction that will provide the most impact. To focus the search, elements of the TRIZ database search strategy are implemented. Steps two and three of the TRIZ database search (EECs and associated principles) are used to narrow the number of products for the search strategy.

The TRIZ database search strategy introduces the concept of environmental engineering characteristics. These are the TRIZ traditional engineering characteristics that are deemed to be the most environmentally friendly. Within this subset of EECs are characteristics that have commonalities, for example the loss of something (time, energy, and information), the production of a product (ease, automation, rates) or energy usage (consumption and loss). These subsets of similar characteristics within the EECs can be used to focus a general product search. This research will focus on finding products that overcome a contradiction to improve performance while reducing energy use. In this way, the strategy for searching the existing TRIZ database is used to focus the field of products. It is possible to focus on a specific set of products instead of having a global marketplace of seemingly infinite amount of products to analyze.

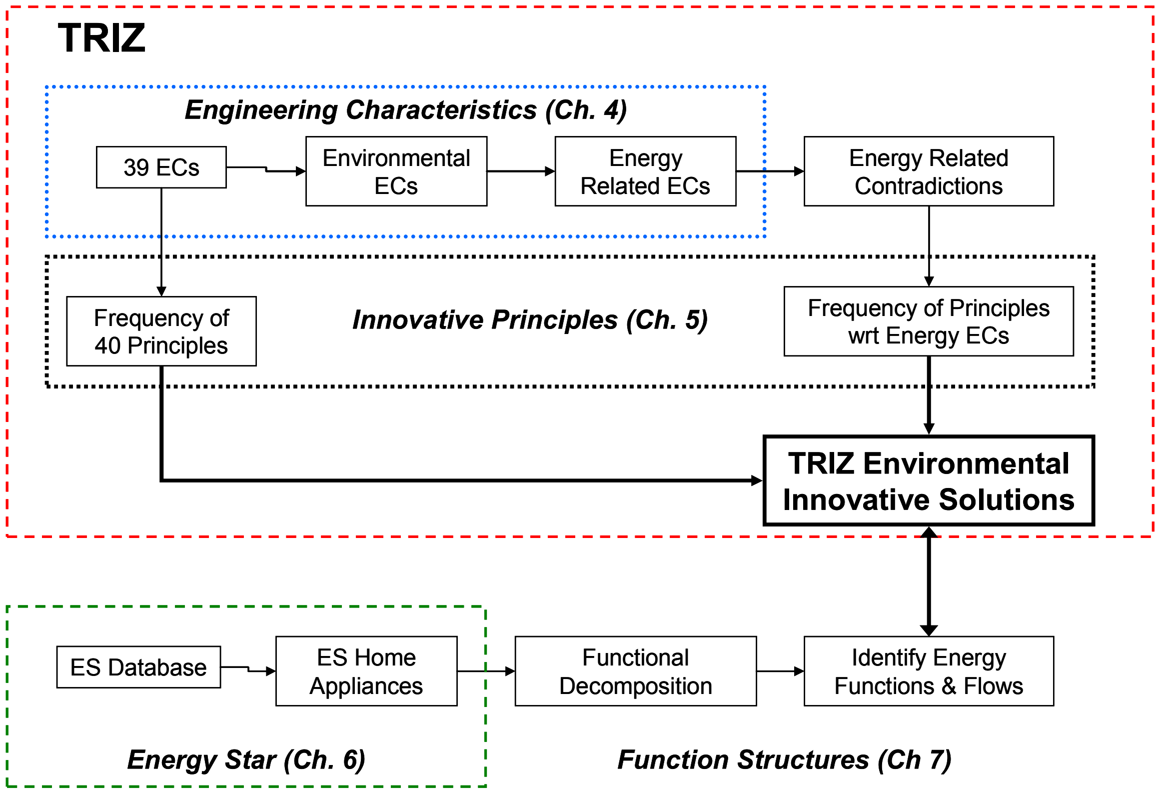


Figure 10: Organizational flow diagram

A flow diagram summarizing the path of this research is provided in Figure 10. The mere addition of adding environmentally benign innovative solutions to TRIZ has been attempted by other researchers and is not sufficient for the next generation of DfE tools. Instead, an analysis of TRIZ characteristics and principles in Chapters 4 and 5 will be undertaken to narrow the product search field to obtain maximum impact on the TRIZ database. In Chapter 6, it will be shown that the ENERGY STAR database is an appropriate source of environmentally innovative products. The choice of function structures as a beneficial representation for ENERGY STAR innovations is demonstrated in Chapter 7.

4 Analysis of TRIZ Engineering Characteristics

There are two major aspects of the TRIZ contradiction matrix that will be discussed in detail: engineering characteristics and innovative principles. There are 39 engineering characteristics (ECs) used in TRIZ (these are listed in Appendix A). The engineering characteristics form the backbone of the TRIZ methodology and the TRIZ matrix. The ECs are used to articulate technical contradictions in the performance of a product. The 39 ECs are arranged on the vertical axis and repeated on the horizontal axis of the matrix. The cell at the intersection of a row and a column holds the set of inventive principles that can be used to overcome the technical contradiction between the corresponding ECs. To find the inventive principles, the designer must determine which engineering characteristic is to be changed and identify the associated row of the matrix. The appropriate column is indicated by the engineering characteristic that is worsening because of this change. For example, one may seek to change the storage capacity of a boat (volume) without increasing the weight of the boat. The language of the engineering characteristics is general so that they can be applied to any design scenario. This also means that same design problem may be articulated with more than one contradiction (multiple pairs of engineering characteristics). For example, if trying to improve the durability of an airplane wing, it is unclear if the wing is a mobile or stationary object. There is a TRIZ characteristic for durability of moving object (EC 15) and durability of a non-moving object (EC 16). To the ground observer, the wing is mobile but when compared to the rest of the plane it is stationary. This is an interpretation issue. A detailed description of the principles will occur in Chapter 5.

The TRIZ engineering characteristics are not explicitly designed for environmental improvement. For TRIZ to become a powerful environmental design tool, the database must contain green products for analogous comparison. It is possible to determine where to focus efforts on expanding the database through analyzing engineering characteristics (EECs) that are more closely related to environmental improvement. This is accomplished through two steps and will aid in narrowing the product search field. The first step is to remove ECs 1 through 14, which reflect the physical nature of a product (size, shape, and weight). The remaining engineering characteristics (15-39) will now be referred to as environmental engineering characteristics (EECs).

The second step is to narrow the product search based on EECs that describe similar types of product performance. For example, EC 22 – Waste of Energy, EC 23 – Waste of Substance, EC 24 – Loss of information and EC 25 – Waste of time refer to the loss of product performance. ECs 29, 32, 37, 38, and 39 refer to manufacturing production performance. The remainder of this work will focus on three EECs that refer explicitly to energy contradictions. They are EC 19 – Energy consumption by mobile object, EC 20 – Energy consumption by stationary object and EC 22 – Energy loss by object. These EECs can be applied to all energy types such as mechanical, thermal, pneumatic and electrical. Internationally recognized environmental metrics do not exist for many of these sources so it becomes difficult to compare improvements. Fortunately, electrical energy does have accepted metrics. The ENERGY STAR certification is obtained only when the product has achieved an environmental improvement in electrical energy consumption. This makes the ENERGY STAR database a repository of environmentally innovative products with respect to electrical energy. Details of the ENERGY STAR database and product information will be provided in Chapter 6.

5 Analysis of TRIZ Principles

To create TRIZ, Altschuller analyzed patents to find commonalities and assigned different levels of innovation. Patents were read, and from them came 40 innovative principles that represent the fundamental ideas that were used to create a new product. The principles provide examples and analogous solutions to contradictions that arise between engineering characteristics. A snapshot of the TRIZ matrix showing the first eight engineering characteristics is shown in Figure 11. Each cell of the matrix corresponds to a contradiction between the improving EC represented in the row and the EC that is worsening in the column. This means that the contents of cell (i,j) has no predictable relationship with cell (j,i). A simple example can be found in Figure 11.

Improving Feature	Worsening Feature	Weight of moving object	Weight of stationary object	Length of moving object	Length of stationary object	Area of moving object	Area of stationary obje	Volume of	V
		1	2	3	4	5	6	7	8
1	Weight of moving object	+		15, 8, 29,34		29, 17, 38, 34		29, 2, 40, 28	
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35	
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2,14
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4	
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+		
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		TRIZ Principles	
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+

Figure 11: Snapshot of TRIZ matrix engineering characteristics 1 through 8 and intersecting cells with numbers corresponding to 40 TRIZ principles [1]

To use the contradiction matrix, an engineer would first determine which EC they wish to improve in the vertical column and then which EC would worsen due to this improvement on the horizontal row. For example, an engineer may want to decrease the weight of a moving object while maintaining a critical area dimension or footprint. Using this matrix the engineer would seek to improve EC 1 - Weight of a moving object at the risk of worsening EC 5 - Area of a moving object. The intersecting cell provides four numbers: 29, 17, 38 and 34. Each of these numbers indicates one of the 40 inventive principles that have been used to overcome the contradiction in a previous case. The complete TRIZ software package provides examples of the prior solutions. An engineer can use these innovative ideas and analogous examples to ascertain a solution to the problem of decreasing weight while maintaining an area.

One unique contribution of this work is a statistical analysis of the frequency of the 40 principles contained in the TRIZ matrix. The goal is to determine which principles appear the most under any of the contradictions (row or column). The frequencies could then be applied to groupings of engineering characteristics such as the environmental ECs or the energy ECs described above. It is unknown if the principles in the cell are of equal weight or are intended to be in order of strength of application, therefore this analysis is independent of a weight factor concerning the order in which the principles appear in the cell.

The list of principles for each of the 39 ECs was recorded in Microsoft Excel and the histogram function was used to visualize the frequency of the principles. An example of a plot that shows the frequency of appearance for each cell in the row and column for

EC1: Weight of Mobile Object is shown in Figure 12. This plot has the 40 principles on x-axis in order and the frequency that each principle appears on the y-axis. It shows that principle 35 – Transformation of Properties appears the most in the cells that correspond to EC1. This type of analysis can provide insight into the most common innovations to solve a contradiction that includes improving or preventing deterioration of an engineering characteristic. Using this information, it is possible to observe the frequency of principles for any combination of multiple ECs.

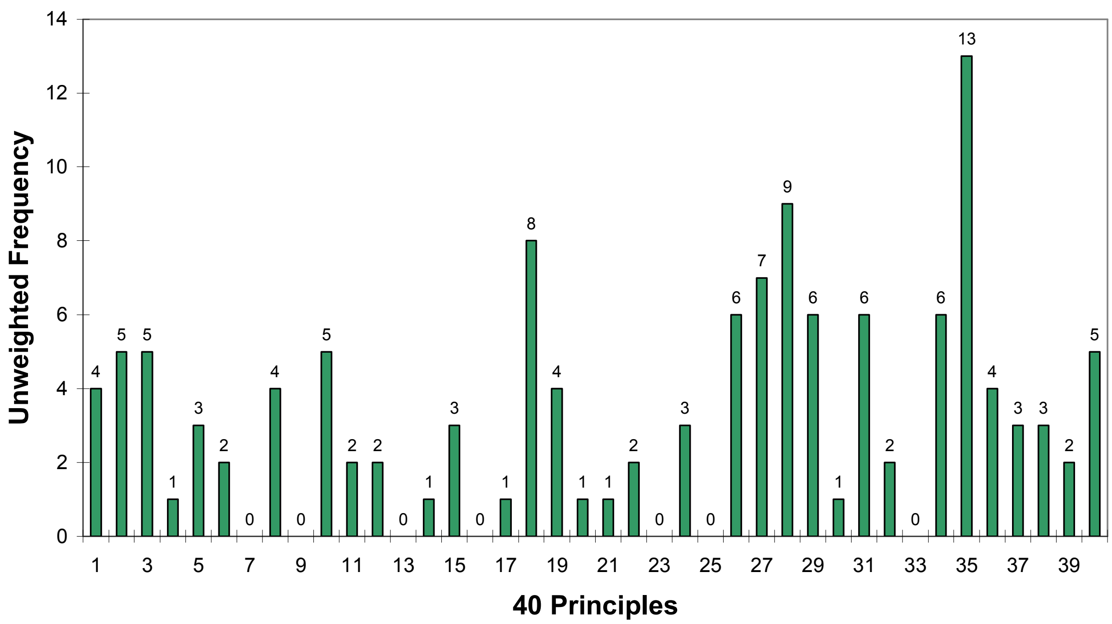
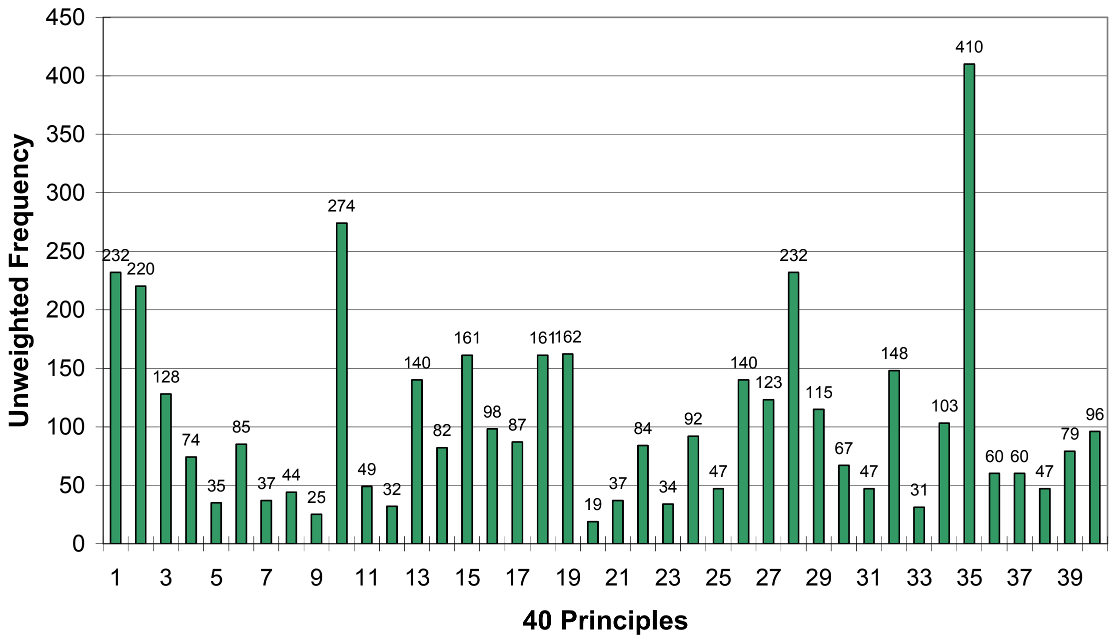


Figure 12: Example of chart showing frequency of 40 TRIZ principles with respect to EC1: Weight of Mobile Object.

5.1 Frequency of 40 Principles in TRIZ Matrix

The first step to observing the frequency of principles for combinations of ECs is to analyze the entire matrix for a baseline comparison. A 39 by 39 matrix contains 1,521 cells where each cell has at most four principles listed, leaving the maximum number of principles as 6,084 principles. The actual number of principles that are contained in the matrix is 4,197. This is because not all the cells contain 4 principles, and some cells do not contain any. A copy of the entire TRIZ matrix can be found in Appendix A. Figure 13(A) shows the principles in order from 1 to 40 on the x-axis and the unweighted frequency on the y-axis for the entire matrix. The average frequency is 102, the standard deviation is 80, and the variance is 6,454. Although these numbers are large they are not surprising because there was never any effort made to evenly distribute the frequencies nor should it be expected. Figure 13(B) lists the top five principles ranked in order of appearance, with principle 35: Transformation of Properties having the highest frequency of 410 appearances while the second ranked principle 10: Prior Action appears only 274 times. Conversely, in Figure 13(C) the five principles with the lowest frequency are listed. Principle 20: Continuity of Useful Action has the lowest frequency, appearing only 19 times in the matrix. Based on these results, principle 35 Transformation of Properties is the most common principle found for overcoming a given contradiction.



(A)

Most Frequencctly Appearing Principles			
Rank	**Frequency**	**Principle #**	**Principle**
1	410	35	Transformation of Properties
2	274	10	Prior Action
3	232	28	Replacement of Mechanical System
4	232	1	Segmentation
5	220	2	Extraction

(B)

Least Frequently Appearing Principles			
Rank	**Frequency**	**Principle #**	**Principle**
40	19	20	Continuity of Useful Action
39	25	9	Prior Counteraction
38	31	33	Homogeneity
37	32	12	Equipotentiality
36	34	23	Feedback

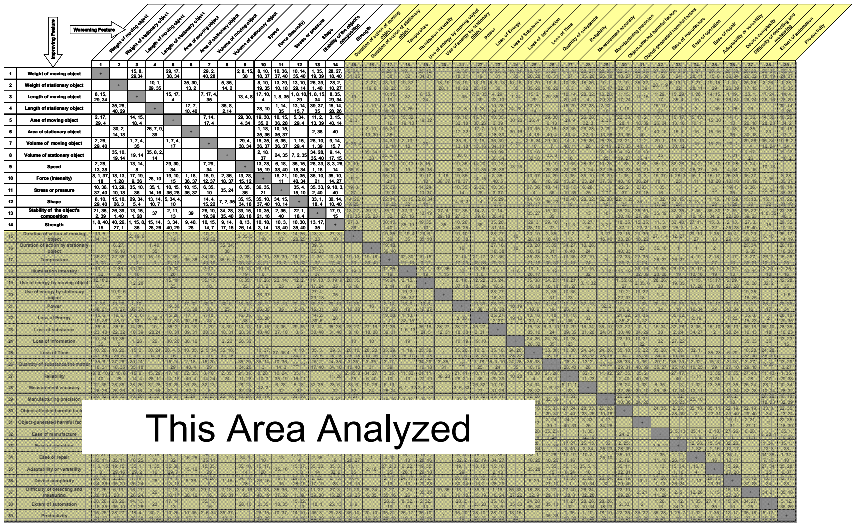
(C)

Figure 13: (A) Frequency of TRIZ 40 principles taken from each cell of the TRIZ Contradiction Matrix and (B) the five principles that appear with the highest frequency (C) the five principles that appear with the lowest frequency

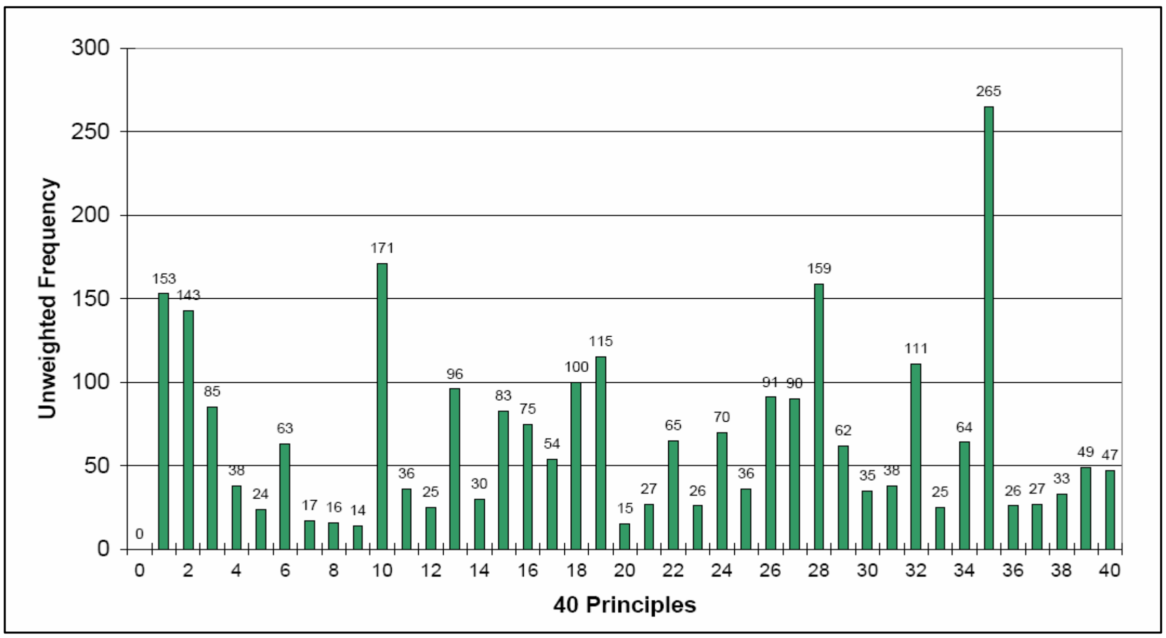
5.2 Frequency of 40 Principles with respect to Environmental Contradictions

Chapter 4 discussed a method to extract the TRIZ engineering characteristics that can be considered more environmental. The goal is to use these environmental engineering characteristics (EECs) to determine if there are some TRIZ principles that are more likely to be used to overcome environmental contradictions. Figure 14(A) shows the entire TRIZ matrix highlighting the analyzed section. The frequency of appearance of each principle in this analysis is shown in Figure 14(B).

From this plot we can again observe a wide variance in frequencies with a few principles appearing significantly more than others. The variance is 2,826. Note that every principle has a frequency greater than one in this analysis. The five principles that appear the most are listed in Figure 14(C). These are the same five principles in the same rank order as in the analysis of the entire matrix. Although 35% of the ECs were eliminated, only 13% of the matrix cells are eliminated. Figure 14(A) shows that only a small portion of the matrix is not being analyzed. Because of this, it is not surprising to observe similar distributions and rankings.



(A)



(B)

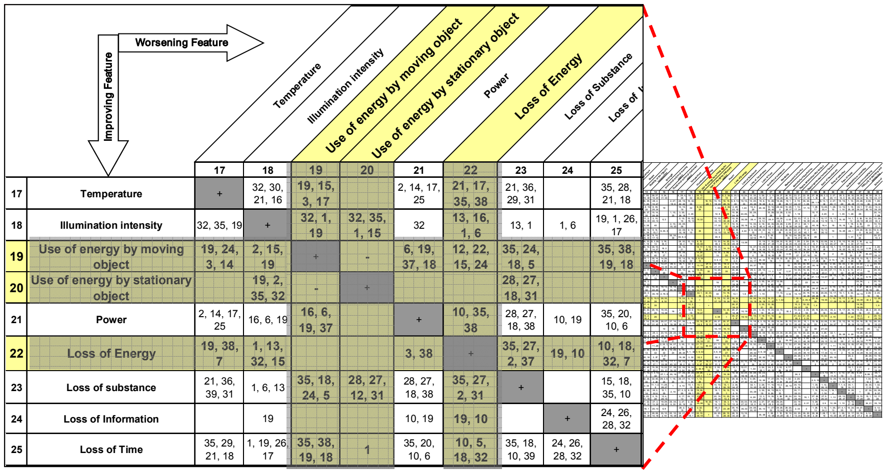
Most Frequently Appearing Principles			
Rank	Frequency	Principle #	Principle
1	265	35	Transformation of Properties
2	171	10	Prior Action
3	159	28	Replacement of Mechanical System
4	153	1	Segmentation
5	143	2	Extraction

(C)

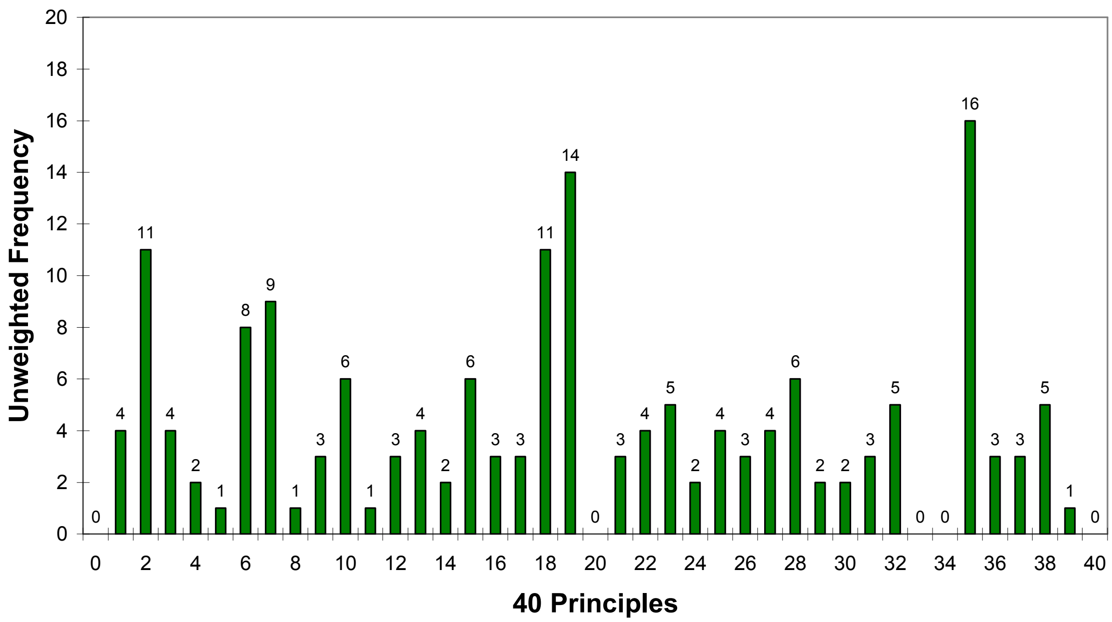
Figure 14: (A) TRIZ matrix with highlighted portion representing the area of analysis. (B) Frequency of TRIZ 40 principles with respect to the Environmental Engineering Characteristic contradictions. (C) The five principles that appear with the highest frequency.

5.3 Frequency of 40 TRIZ Principles with respect to Energy Contradictions

The frequency analysis of the TRIZ principles of the environmental engineering characteristics did not show great difference when compared to the full matrix. Therefore, the focus of the analysis is narrowed to the EECs that correspond explicitly with energy usage. Chapter 4 discussed a subset of the EECs that are directly related to energy contradictions: 19 – Use of energy by moving object, 20 – Use of energy by stationary object and 22 – Loss of energy. Figure 15(A) highlights the portion of the matrix that is being analyzed and magnifies the area where the targeted EECs cross for clarity. The frequency of appearances (y-axis) for the 40 principles (x-axis) of this subset is shown in Figure 15(B). From this figure we can see that there are a few principles that appear more often than the others. We can also observe that there are two principles that do not appear in this subset: 33 – Homogeneity and 40 - Composite materials. The top four principles are listed in Figure 15(C). Principle 35 – Transformation of Properties again has the highest frequency, and principle 2 – Extraction still appears in the top four. This analysis could imply that a search for products that overcome an energy contradiction could mostly contain innovations related to these top four principles. This conclusion cannot be validated at this time but should be revisited as the TRIZ database is expanded.



(A)



(B)

Most Frequently Appearing Principles			
Rank	Frequency	Principle #	Principle
1	16	35	Transformation of Properties
2	14	19	Periodic Action
3	11	2	Extraction
4	11	18	Mechanical Vibration

(C)

Figure 15: (A) TRIZ matrix with highlighted portion representing the area of analysis. (B) Frequency of TRIZ 40 principles with respect to the Energy Saving Characteristics 19, 20 and 22. (C) The five principles that appear with the highest frequency.

6 ENERGY STAR

This research is focused on expanding the TRIZ database to include a specific subset of environmental innovations. There is no mass environmental product database that exists within the scope of this definition of green. Therefore, a database must be created within the TRIZ methodology. Although the TRIZ database may already contain environmental innovations, it is difficult to identify them through the current methods. Search strategies were created to find green products that would build the database. A method was described that would narrow the search to products that overcome an energy contradiction. Energy contradictions could refer to thermal, mechanical, pneumatic, human and electrical. The ENERGY STAR database provides a detailed description of green products with respect to electrical energy consumption. For this reason, the ENERGY STAR database has been selected as the primary source of product identification for this work.

ENERGY STAR is a certification for products that meet specified energy consumption rules. In this way, ENERGY STAR has created a metric for environmental innovation. The metrics are constantly updated both as a reaction to the changing industry and also to drive innovation. The databases of products that are ENERGY STAR rated are in the public domain and can be found at www.energystar.gov [2]. In terms of this work, analyzing products that have achieved ENERGY STAR certification involves looking specifically at the contradictions among three environmental engineering characteristics, which are: 19 - Energy spent by moving object, 20 - Energy spent by non-moving object and 22 - Waste of energy.

From the ENERGY STAR Website:

> ENERGY STAR is a joint program of the U.S. Environmental Protection Agency and the U.S. Department of Energy helping us all save money and protect the environment through energy efficient products and practices. Products in more than 50 categories are eligible for the ENERGY STAR. They use less energy, save money, and help protect the environment. ENERGY STAR products are the same or better than standard products, only they use less energy. To earn the ENERGY STAR, they must meet strict energy efficiency criteria set by the US Environmental Protection Agency or the US Department of Energy. Since they use less energy, these products save you money on your electricity bill and help protect the environment by causing fewer harmful emissions from power plants. And you get the features and quality you expect.

ENERGY STAR is a voluntary program where companies can submit products for certification. As more products meet the ENERGY STAR standards the requirements for certification must be raised.

ENERGY STAR certification assures compliance with energy savings criteria. However, not all products in the database contain a significant innovation. Despite major innovations seeming like they appear from nothing, there are generally years of minor improvements made between a large innovations. These small improvements in sensors or efficiency are what allow products to continue to meet the ENERGY STAR requirements. Figure 16 is a timeline of some major innovations in household appliances since 1900. This shows that important innovations are spread apart over several years. ENERGY STAR is one part of a large effort made by the government to increase environmental awareness in industry and reward organizations that make efforts to improve their products.

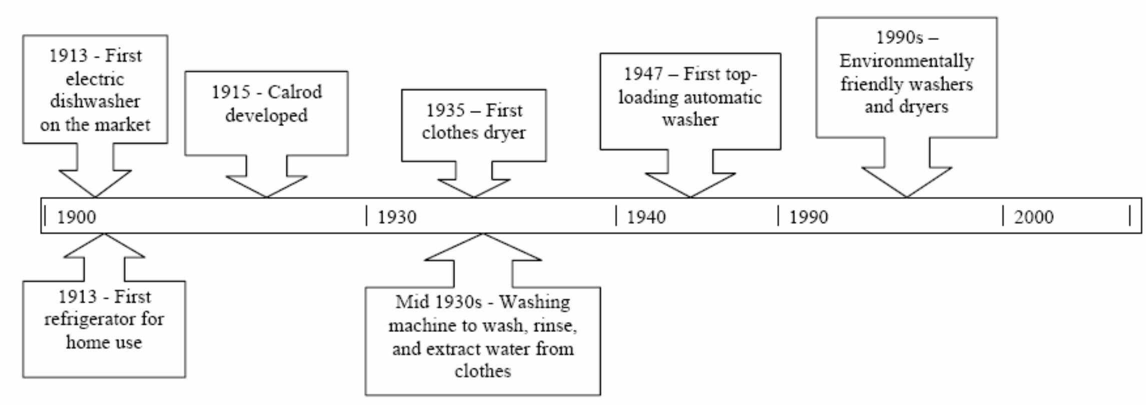


Figure 16: Household appliance timeline of product introductions and innovations [35]

6.1 ENERGY STAR Categories

ENERGY STAR is divided into eight product categories:

1. Appliances (8)
2. Heating & Cooling (12)
3. Home Envelope (3)
4. Home Electronics (9)
5. Office Equipment (11)
6. Lighting (5)
7. Commercial Food Service (4)
8. Other Commercial Products (8)

Each category is then divided into product classes such as Central AC, Furnaces and Boilers for Heating & Cooling Category. The number of product classes in each category is shown in parentheses in the list above. Each category contains products that are available in industry that meet the ENERGY STAR metrics of energy usage. The metrics are different for each class and category and are derived from the existing products and the trends of energy usage. The following sections will discuss the Appliance category in detail including metrics for the product classes and the number of companies and products certified.

Any organization can have its products ENERGY STAR certified if the criteria are met. The company must first join ENERGY STAR, which is free and voluntary. Then, the company can submit products for testing and certification or go through steps to test internally and submit the findings for approval. The products must meet the specifications laid out by ENERGY STAR. Examples of these specifications for some appliance classes can be found in Appendix D. Once certified, a product will always have the ENERGY STAR tag regardless of increased specifications. However, a company must continue to meet specifications with each new product line. The details of the specifications that must be met for ENERGY STAR home appliance products as of December, 2006, will be discussed in further detail in the following sections.

6.2 ENERGY STAR Appliances Category

The ENERGY STAR Appliance category is divided into eight product classes:

1. Battery Chargers
2. Clothes Washers
3. Dehumidifiers
4. Dishwashers
5. Refrigerators & Freezers
6. Room Air Conditioners
7. Room Air Cleaners
8. Water Coolers

Five of these eight classes will be considered for this research: clothes washers, dehumidifiers, dishwashers, refrigerators and room air conditioners. Information regarding the ENERGY STAR selection criteria for some of these product classes is outlined in Appendix D. The important metric for all ENERGY STAR certified products is a variation of an Energy Factor (EF). The energy factor varies between product classes but always refers to the amount of energy used per unit time or operation. Different equations are derived based on this concept so that multiple styles of products can be compared. For example, clothes washers are evaluated based on a Modified Energy Factor (MEF) that accounts for different capacity and is expressed as ft^3/kWh/cycle. These tables also show a comparison between Federal standards and ENERGY STAR standards.

The following sections will review the companies and products that are ENERGY STAR certified in five of the appliance classes. Information will also be given on patent classifications for each product class because TRIZ has historically been based on innovative patents. In current business practices in the United States, corporate strategies separate production and patenting. This means that not all products that contain environmental improvements will be patented and not all patents will be produced. The dishwasher class will be discussed in more detail to demonstrate trends that are observed in the ENERGY STAR database that could inflate the number of models reported.

6.3 ENERGY STAR Dishwashers

Dishwashers have become a common appliance in most residential homes. A patent search was conducted to gain insight into possible innovations. Dishwashers can be found within the patent class “D32/2: Washing, Cleaning, or Drying Machine: Dishwasher type.” Since 1898, 109 patents have been issued in this patent class. Other patent classes for dishwashers include but are not limited to CCL/D32/:

8: Dryer or Extractor

22: Upright Type
26: Agitator
27: Wringer
29: Tub or Drum

ENERGY STAR qualified dishwashers use 25 percent less energy than the federal minimum standard for energy consumption. They are evaluated based on an energy factor (EF), which is calculated as the "estimated loads per year (215 loads)" divided by "the annual energy usage (kWh/yr)". The energy factor federal standard in 2006 was 0.46 or an annual energy usage of 467.4kWh/yr. Dishwashers that were certified in 2006 had to meet or be higher than the 0.46 standard. This would imply that they would use less than 467.4kWh/yr for 215 loads.

There are currently 49 companies that have ENERGY STAR-certified dishwashers, totaling 734 products. The distribution of products per company is shown in Figure 17, which shows a table of the companies that offer the most ENERGY STAR products and a chart showing the percentage of the total product base offered by different companies. This figure shows that 16 percent (119 models) of ENERGY STAR certified dishwashers are sold by Kenmore, 15 percent (109 models) by Bosch, and 9 percent (64 models) by Frigidaire. The "Other" category in Figure 17 contains 48 percent of the products from 44 companies that offer less than 30 models per company.

Kenmore	119
Bosch	109
Frigidaire	64
General Electric	53
Whirlpool	38
Maytag	32
Miele	28
etc.	291
Total	**734**

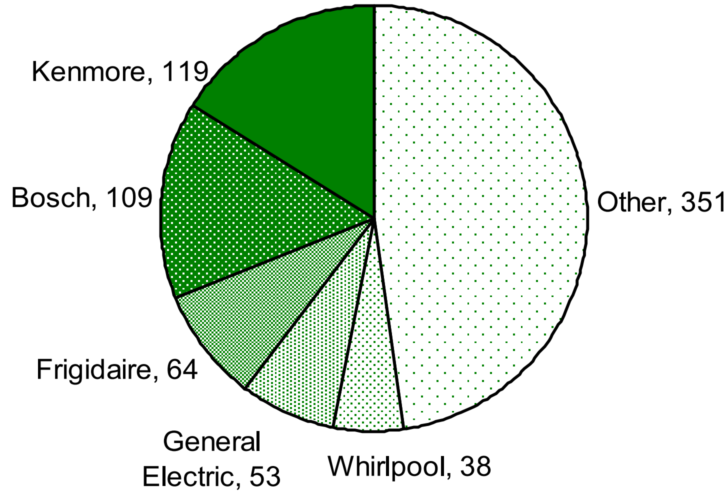


Figure 17: Distribution of ENERGY STAR-certified dishwasher models sold by a company. Sixteen percent of all ENERGY STAR Dishwashers are sold by Kenmore, 15% Bosch, etc. 'Other' category includes 44 companies that offer less than 30 dishwasher models per company.

The number of products produced by each company may be inflated due to the method used to label different models. For example, Kenmore offers 119 models that are ENERGY STAR certified, however, the same product may be listed as multiple colors (white, black, stainless steel and custom.) thus inflating the true number of products offered. The first step to filtering the ENERGY STAR database was to eliminate products that were no longer produced. Then each product was found through an Internet search to eliminate products that were mechanically identical and had the same activation date. To illustrate this repetition and provide insight into the true number of mechanically different product lines, the Kenmore and Bosch dishwasher products will be evaluated at a deeper level.

6.3.1 Kenmore Dishwashers

Kenmore leads all companies by offering 119 different models of ENERGY STAR-certified dishwashers. The Kenmore models listed from the ENERGY STAR database are 26% to 41% better than the current federal standard. A portion of the list provided by the ENERGY STAR Website is provided in Appendix D, Table 13. The first step to creating a realistic view of the database was to eliminate models that are no longer active, which removed 36 models. This includes models that were once ENERGY STAR certified but are no longer advertised or produced. The next step was to eliminate models that could not be found through the company website, company catalogs and sales catalogs. This eliminated an additional 54 models. The remaining 29 models were sorted based on activation date, color and product description. Models that were identical in all categories except color were removed, revealing there were only three major products:

- 24 in. Built-In Dishwasher with 5-level Precision Wash System
- 24 in. Built-In Dishwasher with AutoSensor™ Wash System
- 24 in. Built-In Dishwasher with Hi-Temp Wash Option

This analysis shows that although Kenmore only offers three distinct product models, although being listed as providing the most dishwasher models (119) of any company in the ENERGY STAR database. This is not a deceptive strategy by the corporation because ENERGY STAR requires that all models must pass tests in order to be certified. ENERGY STAR does not account for aesthetic differences within this requirement. To further show this trend of inflated numbers, a second company was analyzed in more detail.

6.3.2 Bosch Dishwashers

Bosch offers 109 models of ENERGY STAR rated dishwashers which are between 26% and 61% better than the federal standard. The 50 models that were no longer offered or could not be located through search methods were removed. The remaining models were researched in more detail to reveal 19 models that were mechanically different. These models are grouped into two different categories, each with three series:

- Integra 800 Series, 500 Series and 300 Series
- Evolution 800 Series, 500 Series and 300 Series

This further supports that the number of product models provided by the ENERGY STAR database does not refer only to mechanical differences but also to aesthetic differences.

6.4 ENERGY STAR Refrigerators and Freezers

ENERGY STAR qualified refrigerators are required to use at least 15 percent less energy than federal standards and 40 percent less than conventional models from 2001. ENERGY STAR freezers must use at least 10 percent less energy than federal standards. Refrigerators can be found in the patent class 62/3.6: Refrigeration: Interior of enclosure cooled; e.g., refrigerator. There have been 155 patents issued in the classification since 1975. An additional class that could contain patents relevant to household refrigerators is 165: Heat Exchange.

Kenmore	364
General Electric	195
Frigidaire	175
Whirlpool	166
KitchenAid	135
Maytag	110
Etc.	582
Total	**1727**

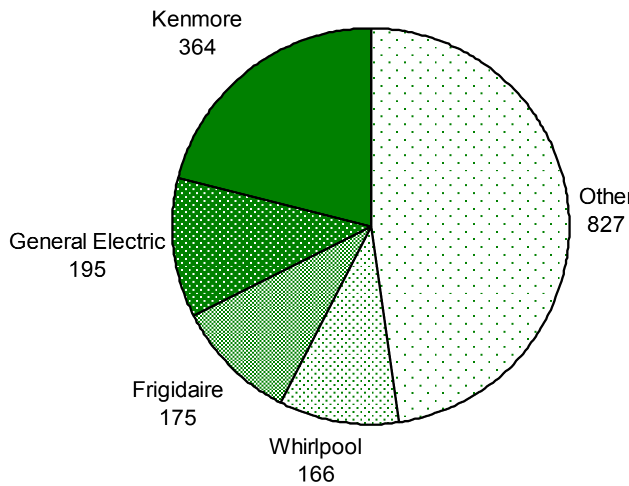


Figure 18: ENERGY STAR Refrigerators & Freezers Company Distribution

There are currently 59 companies that have ENERGY STAR-certified dishwashers, totaling 1,727 product models. A table of the companies that offer the most ENERGY STAR products and a chart showing the percentage of the total product base offered by different companies is provided in Figure 18. Kenmore offers the most ENERGY STAR-certified refrigerators with 21 percent (364 models) while General Electric offers 12 percent (195 models) and Frigidaire offers 10 percent (175 models). The "Other" category in Figure 18 contains 48 percent of the products which are 55 companies.

6.5 ENERGY STAR Clothes Washers

ENERGY STAR-certified clothes washers range between 35% and 168% better than federal standards through the use of energy saving techniques including sensors and controllers. According the ENERGY STAR website, using a certified clothes washer can save up to $110 per year in electric utility bills. Clothes washers are evaluated based on a modified energy factor (MEF) in order to compare efficiency of washers with different volume capacities; see Appendix D, Table 10: ENERGY STAR Metrics for Clothes

Washers. Patents regarding clothes washers can be found in patent class D21/1: Washing, Cleaning or Drying Machine. There have been 186 patents issued in this class since 1977. In addition, there may be relevant patents in additional D32 subclasses. For a full list please see Appendix D, Table 12: Company, Product and Patent Information for ENERGY STAR Database.

Kenmore	75
Frigidaire	44
Maytag	31
LG Electronics	25
Whirlpool	22
General Electric	22
Other	122
Total	**341**

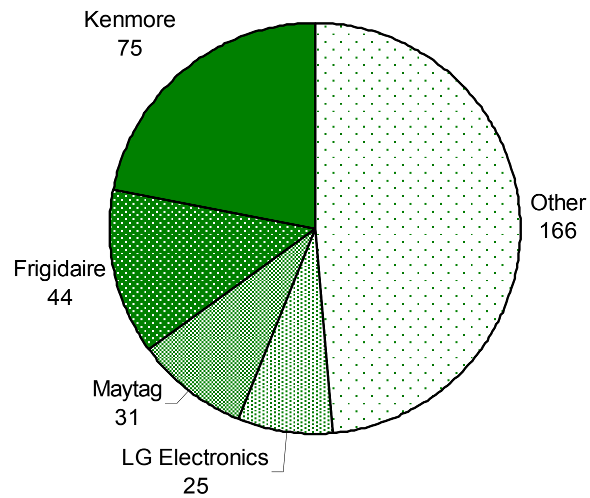


Figure 19: ENERGY STAR Clothes Washers Company Distribution

There are 33 companies that offer ENERGY STAR certified clothes washers totaling 341 products. The breakdown of the company totals and percentages are shown in Figure 19. Kenmore offers the most clothes washers with 75 models (22%) while Frigidaire is a distant second with 44 models (13%). The "Other" Category contains 26 companies that offer between 1 and 22 models and makes up 47 percent of the product base.

6.6 ENERGY STAR Room Air Conditioners

ENERGY STAR-certified room air conditioners are comprised of timers or more sophisticated sensors to reduce the length of time that the product is in use. Certified units are between 10 percent and 33 percent more efficient than current federal standards.

Air conditioners are measured by an energy efficiency ratio (EER) which is the ratio of the cooling effect and the consumption of electrical energy. A full list of criteria and standards for air conditioners is provided in Appendix D, Table 8. The patent class most relevant to room air conditioners is class 62/262: Refrigeration: Window connected or mounted. There have been 234 patents issued in this class since 1974.

Friedrich	122
Frigidaire	99
General Electric	96
Kenmore	40
Panasonic	38
Whirlpool	36
Other	331
Total	762

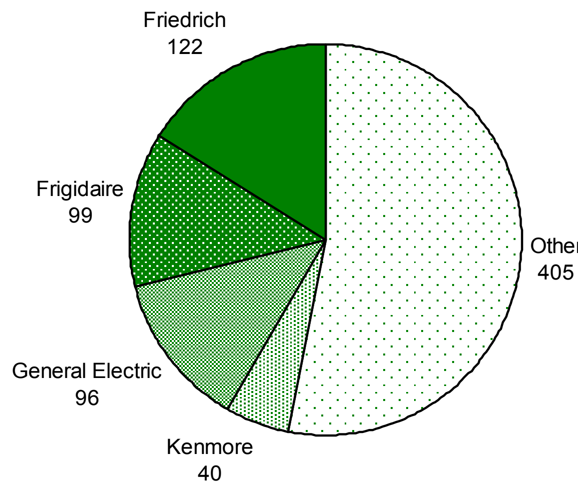


Figure 20: ENERGY STAR Room Air Conditioner Company Profile

A search in the ENERGY STAR database revealed 762 models of room air conditioners offered from 34 companies. Figure 20 provides a breakdown of the top companies and number of models offered. Friedrich offers the most certified models with 122 (16%) while Frigidaire offers 99 models (13%). The “Others” category in the pie chart comprises 30 companies offering a total of 404 models.

6.7 ENERGY STAR Dehumidifiers

According to the ENERGY STAR website, certified dehumidifiers operate at 10 percent to 20 percent better efficiency than standard units. The criterion for the energy factor for dehumidifiers varies for different capacities, which makes selecting the proper product important to reduce energy consumption. A product that is too large for a room will use more energy than necessary while a product that is too small will not provide the required performance. The website also provides tools to determine the optimal dehumidifier for a given room size, temperature and humidity level. This provides consumers with information to choose the proper dehumidifier to maximize the way energy is used. A description of the ENERGY STAR standards and definitions is provided in Appendix D, Table 9. Patents regarding dehumidifiers can be found in the class D23/359: Environmental Heating and Cooling; Fluid Handling and Sanitary Equipment/Dehumidifier. This class has had 24 patents issued since 1976, the fewest of any class discussed in this work, which could imply that there is room for innovation. There are also functions of dehumidifiers that have patents found in class D23/314: Heating or Cooling.

LG Electronics	68
Midea USA	30
Haier America	18
De'Longhi America	15
Other	67
Total	**198**

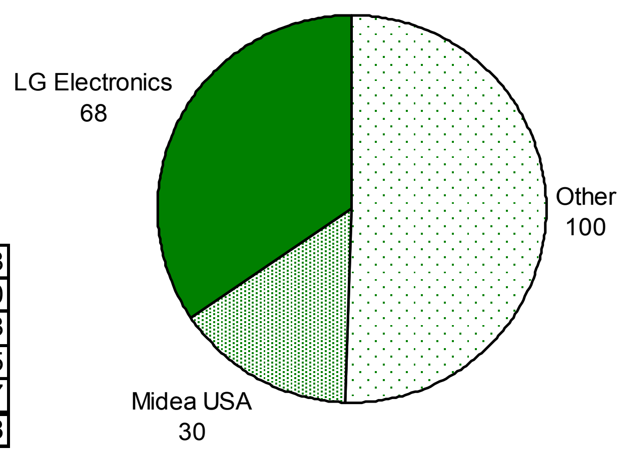


Figure 21: ENERGY STAR Dehumidifier Company Distribution

There are only 15 companies that offer ENERGY STAR-certified dehumidifiers. The breakdown of companies and offered models is found in Figure 21. LG Electronics offers the most certified models with 68 (34%) while Midea USA offers 30 models

(15%). The "Others" category in the pie chart includes 13 companies offering a total of 100 models.

7 Using Functional Models to Identify Design Contradictions

A key contribution of this research is using function models to identify and characterize technical performance contradictions in terms of TRIZ engineering characteristics. This chapter will provide examples of ENERGY STAR appliance function models. It will be shown that function models can be used in the TRIZ methodology to generate innovative concepts across product families.

7.1 ENERGY STAR Appliance Functional Decomposition

It is possible to identify areas of environmental design improvement through observing the electrical energy flow paths of ENERGY STAR product functional models. There is an opportunity for improvement at each intersection of the flow with a function block because it is the location that a flow is being modified. If these opportunities can be stated in the form of a contradiction between an improving EC and one that is worsening because of that improvement, then TRIZ can be used to provide analogous solutions to the function group.

Recall that this research is focused on environmental improvements that overcome an electrical energy contradiction. The function structures of a household dishwasher, clothes washer, clothes dryer and refrigerator are found in Appendix C. Each of these figures highlights the electrical energy flow paths and the function blocks at which the flow is changed from electrical to another form of energy such as thermal or mechanical.

The clothes washer and clothes dryer also highlight signals that exist in the process that apply to the electrical energy flow.

These function structures can be examined to obtain contradictions leading to innovative principles using TRIZ. The first example will be of a clothes dryer sensor. The second will be clothes washing machine. For the cases of improving environmental impact by reducing energy usage, the purpose of the function block will be the area of improvement and reducing energy usage will be the EC that would get worse.

Companies are constantly seeking improvements in product performance to remain competitive in the market. ENERGY STAR certification has become a differentiation mark for consumers. At the same time, the ENERGY STAR criteria are constantly shifting upwards to drive environmental improvements. One cannot prove a causal relationship here, but it may be that smaller design innovations will motivate companies in the future to continue seeking certification on new models. Therefore we assume small advances are made to products that may not be substantial mechanical innovations but still reduce electrical energy consumption.

In recent years, progress has been made to incorporate new sensors and controls systems to tightly control electricity usage. Sensors and control systems appear in function structures in subsystems where electrical energy is being controlled, not converted. The function block representation of a control system will use function blocks such as actuate, control, regulate and sense. Part of a function structure of a clothes washer is shown in

Figure 22. Both actuate and regulate function groups indicate the presence of a sensor or controls system for electrical energy. The first time a sensor or controls system was used in this design it would have changed the function structure to include this group. A change in function structure would signify a significant innovation for that product. TRIZ inventive principle 23 – Feedback would suggest the use of a sensor in the system. In the same way, applying TRIZ inventive principle 23 would lead a designer to add a sensor into the system. In either case, the change in the function structure would be the same.

This work uses the functional model representation of products to provide easier application of an innovation to a new concept. Although two products have different performance goals, the electrical energy functional flows can share common paths. Figure 22 and Figure 23 show a small part of the electrical energy flow in a clothes washing machine and a clothes drying machine. In both systems, the energy is imported, then actuated and then regulated. This is a common series of flow for many household products that rely on electrical energy. In fact, the latest generation of electrical products in the market feature sophisticated control technologies in an attempt to save electrical energy and improve performance.

This proposed extension to TRIZ would provide the designer with the function structure snapshot for the addition of a control system. With this extension, an innovation that occurs in a function group for a clothes washing machine could be applied to a similar function group in a clothes drying machine. Recognizing the similarity of the innovation is easier when it is expressed in functional terms that the designers use to conceptualize the product (i.e. a function structure) than when a verbal phrase is given "Feedback."

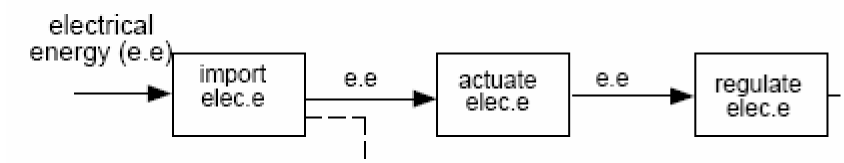


Figure 22: Snapshot of function structure for a clothes washing machine [24]

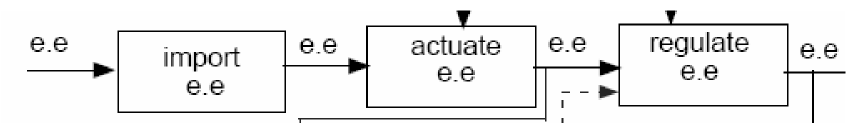


Figure 23: Snapshot of function structure for a clothes drying machine [24]

The greatest opportunity for environmental impact occurs when an energy flow is converted into a different flow. Functions of convert are highlighted in the function models in Appendix C. The function blocks symbolize standard components. For example, when electrical energy is converted to mechanical rotational energy, it is referring to an electric motor. Motors are continuously being upgraded so that they can provide the same performance while becoming lighter and smaller and using less energy. Innovations within the functional class "convert" can provide the most impact on energy usage. The function models of a dishwasher, refrigerator and clothes dryer all convert electrical energy to thermal energy. A significant environmental improvement in this function class could be applied across multiple product families based on the function structures.

7.2 Energy Related Conceptual Design Opportunities Using TRIZ

This section will apply the process of using function models to identify design contradictions of the ENERGY STAR home appliances. Specific examples of applying TRIZ to provide concepts for small energy improvements and higher impact innovations will be shown for a clothes dryer and clothes washing machine (respectively). This will illustrate the importance of abstracting a product to the functional level in order to determine innovative solutions.

Clothes dryers tumble clothes under different heat settings for some period of time in order to remove moisture after washing (or in some cases to remove wrinkles or heat already dry clothing). In the past, dryers operated on a timer that the user would set and the dryer would operate until time ran out. This was an inefficient use of electricity because dryers would continue to operate independent of the dryness of the clothing. Recently, dryers began to use settings that were based on dryness level instead of time. This improvement would cause the dryer to stop when clothes were dry. The portion of the electrical energy flow under consideration is shown in Figure 24.

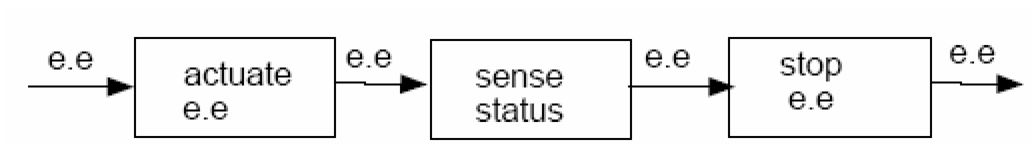


Figure 24: Portion of function structure of clothes dryer [24]

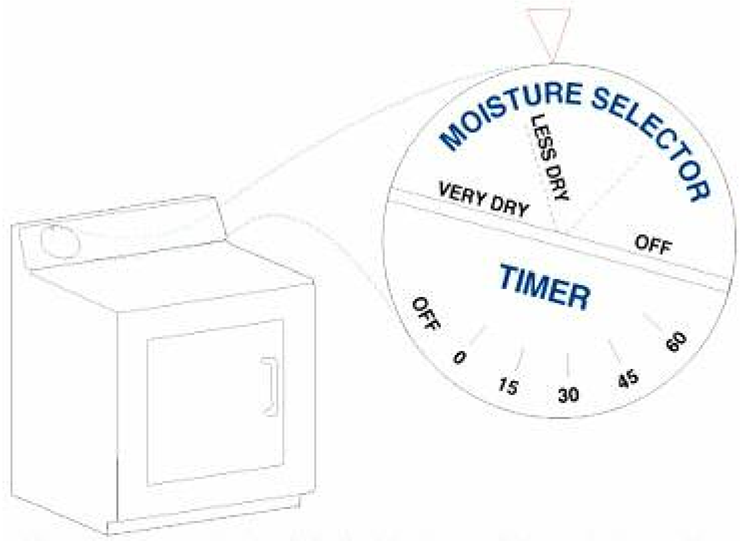


Figure 25: Moisture Settings for clothes dryer [36]

The subsystem would sense the humidity within the clothes compartment and turn off the dryer at a certain point, Figure 25. TRIZ promotes the “ideal product” as a system that operates “by itself.” In this case, the dryer is deciding when to turn off by itself. TRIZ could be used to apply this concept to other products that replace timers with sensors to reduce energy consumption or share a similar function flow. Using TRIZ terminology, there is a contradiction between increasing the level of automation (EC 38) and losing energy by the object (EC 22) for which the TRIZ matrix provides innovative principles 23-Feedback and 28-Replacement of Mechanical System. This sensor system is an analogous solution that would most likely be found in the feedback principle. Through using TRIZ, a designer can find and use this innovation and apply it to any product family on any scale.

Adding sensors and gauges to a product shows how small improvements can be made to reduce the use of wasted electrical energy. More substantial energy reduction innovations occur in the function blocks where electricity is converted into a different energy (such as thermal, rotational, or pneumatic.) An example of this form of innovation was the introduction of the top loading clothes washing machine. The purpose of this mechanical innovation was to allow the centrifugal force from spinning the clothes compartment to remove excess moisture due to washing. The function structure of this phase of the washing cycle is shown in Figure 26. The oscillatory energy (o.e.) that enters the function block is produced through the rotational energy that is converted from the electrical energy. It stands to reason that reducing the oscillatory energy will reduce the energy consumption.

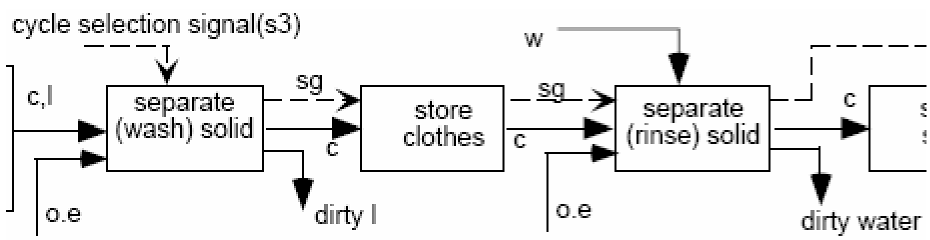


Figure 26: Portion of function model of a clothes washer [24]

The contradiction between reducing electrical energy while improving the effect of the oscillatory energy can be described as improving the force exerted by object (EC 10) while decreasing the energy consumed by mobile object (EC 20). The TRIZ matrix provides principles 19-Periodic Action, 17-Transformation into a New Dimension and 10-Prior Action. The idea of changing the axis of rotation from horizontal to vertical would be found within principle 17-Transformation into a New Dimension. This would allow a designer to observe a similar function structure of separating a liquid from a solid and apply it to a different product family.

7.3 Using Expanded TRIZ Database for Conceptual Design

Once an environmental database is constructed, it will be possible for designers to use TRIZ to find analogous solutions to environmental problems on a functional level. Figure 27 shows a method of manipulating the problem scenario to make best use of the functional models and environmental innovations in the new database.

The scenario should be broken down and abstracted to create a functional model (1). Any contradiction or opportunity for innovation should become apparent as a specific flow or class or a group of flows (2). An example of an opportunity for innovation is a function class that converts one form of energy into a different form of energy (converting thermal energy into rotational energy). The functional model does not provide mechanical solutions to the problem but will help the designer determine the engineering characteristics that are involved in the function flows. One contradiction may be obvious but many times there will be multiple ECs and contradictions that have to be analyzed. The existing TRIZ database is used to produce a set of principles (3,4). Within those principles should be the existing TRIZ database and a set of products that have functional models. The function structures can be compared to find similar flows and classes (5). The function groups are used to locate products and innovations independent of the system to which they belong. The innovations in these products can be applied to the existing problem scenario in attempts to find an analogous solution (6).

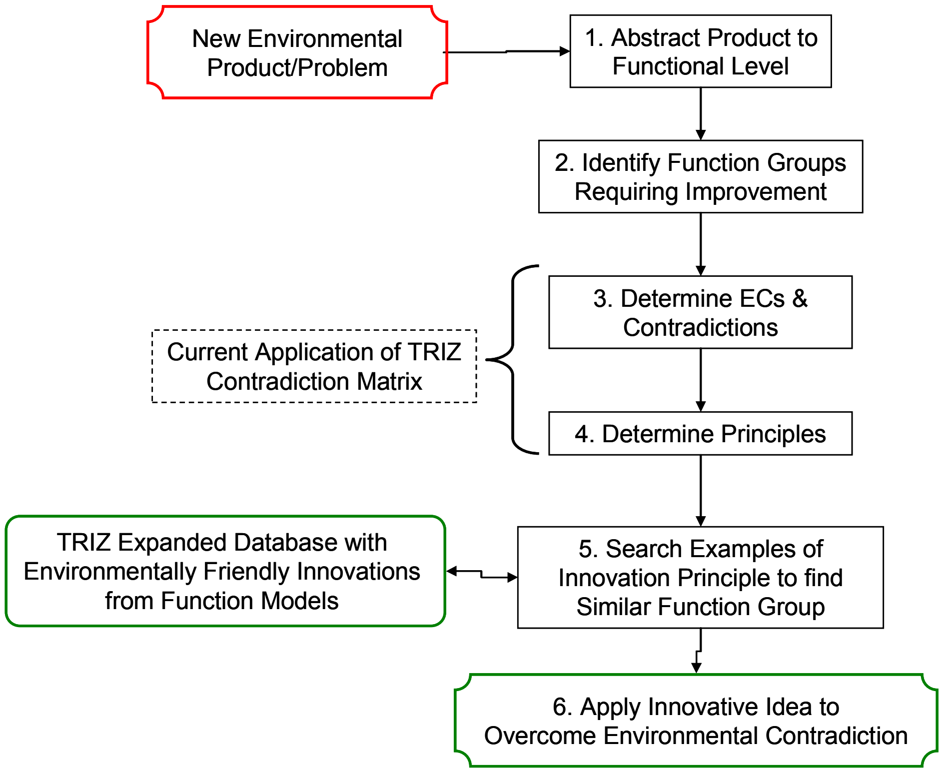


Figure 27: Method of using an expanded TRIZ database to solve environmental contradictions on the functional level

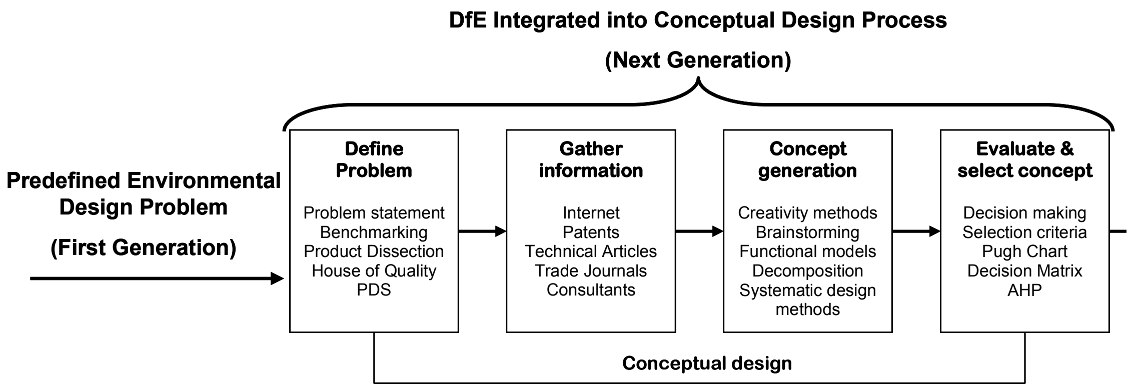


Figure 28: Expanded TRIZ Method Applies in Conceptual Design

Recall the discussion in sections 1.2 and 1.3 about the different generations of environmental design. The method described in Figure 27 is applicable for both generations of designs. If a design problem is formed to specifically overcome an environmental technical contradiction than the TRIZ methodology can be immediately in the conceptual design process, see Figure 28. Because the problem is inherently environmental, TRIZ can be explicitly used as a valid environmental design method.

The next generation of environmental design would not require a problem to be predefined as environmental, as shown in Figure 28. The TRIZ methodology would encompass the conceptual design phase. The process of creating a product function structure and determining the contradictions and principles would be part of the definition and information gathering stages of the conceptual design process. In the next generation, environmental design will be part of the standard practice. The work in this section has demonstrated how one could use ENERGY STAR product categories to find innovations to add to the TRIZ database.

8 Contributions and Future Work

A new understanding of the environmental impact of technology has emerged in the last 50 years. Pollution from production and consumption is at an all-time high. Addressing environmental considerations during the design of new products is becoming essential in today's dynamic market. The motivation for this work reflects the efforts that are being made in research and industry to become more environmentally conscious. While it is important to understand that the best air purifier is to avoid polluting the air in the first place, if air purifiers are needed, then should use the least amount of energy and be as environmentally benign as possible. The best way to imbed DfE guidelines into new product development is to infuse the process with environmentally benign alternatives at each step. The goal of the DfE is to make all design environmentally benign design in the same way that all design is cost effective design for today's corporate engineer.

The ENERGY STAR database is used in this work because it is considered a symbol for environmental progressive products. The ENERGY STAR criteria both drive innovation and react to improvements. They are based on limiting certification requirements to a certain percentage of products, and they increase only when the percentage of certified products approaches a critical value. The primary drive for environmental improvement within ENERGY STAR products is the competition between companies in the market. While ENERGY STAR is a valid source for energy-saving products, it does not act as the driving force behind significant innovations. That level of information is obtained only by viewing the research laboratories at companies that are developing the next generation of dishwashers and refrigerators. For now, the minor improvements due to better sensors and more efficient motors are the sources of environmental improvement.

8.1 Contributions

There are three contributions of this work:

- The first contribution is the analysis of the relative frequency of TRIZ principles for combinations of engineering characteristics within the TRIZ contradiction matrix. This provided insightn ito the more common innovative principles for specified design scenarios.
- The second contribution is the use of function models, according to the function basis developed by Otto and Wood, to characterize technical performance contradictions in terms of TRIZ engineering characteristics and to identify environmental innovations in existing designs. This is important because mechanical engineers think in functions and also because the ability to search the subset of solutions the TRIZ database by function is more useful in conceptual design.
- The third contribution has provided support to the research to validate the expansion of the TRIZ database using certified green products and functional modeling. This was demonstrated by examining electrical energy saving household appliances and detailing the process by which they can be added to the TRIZ database. This Demonstrated that function structure similarities can be used to identify opportunities for electrical energy saving innovation from one product family to another.

8.2 Future Work

The research on how to create the expanded TRIZ database has been completed and verified. What is left is to populate the database. The next step in populating the expanded TRIZ database for environmentally benign products is to apply the method outlined in Figure 27 to the five categories in ENERGY STAR appliances identified in Chapter 6. The utility of the new database can be verified by using it to generate new conceptual designs for the next level of environmentally friendly models of home appliances.

Work is being conducted that involves restructuring the ARIZ process and the language in the TRIZ matrix specifically for environmental design (ENVRIZ)[16]. The definitions, functional models and product search strategies presented in this work should provide valuable information for building the ENVRIZ methodology. Further research is being done on building a language for function structures. A novel idea would be to use function models as a basis for searches. The efforts made in using function models for innovative comparison of products is not limited to environmental design or the TRIZ methodology; rather, functional models can be used in any design process to better understand the fundamental purpose of a system. These models can produce commonalities in systems that would not otherwise be apparent.

Finally, it should be known that this work is merely the beginning of a long line of research focused on improving concept generation and increasing the environmental awareness of an engineer. In the spirit of TRIZ, the ideal design for environment method is to have no method at all because it is so integrated into the development process.

Corporations drive change in the market, while engineers drive innovation in the products.

Appendix A: TRIZ Contradiction Matrix

Worsening Feature →
Improving Feature ↓

	Improving Feature	1 Weight of moving object	2 Weight of stationary object	3 Length of moving object	4 Length of stationary object	5 Area of moving object	6 Area of stationary object	7 Volume of moving object	8 Volume of stationary object	9 Speed	10 Force (Intensity)	11 Stress or pressure	12 Shape	13 Stability of the object's composition	14 Strength	15 Duration of action of moving object	16 Duration of action of stationary object	17 Temperature	18 Illumination intensity	19 Use of energy by moving object	20 Use of energy by stationary object
1	Weight of moving object	+		15, 8, 29, 34		29, 17, 38, 34		29, 2, 40, 28		2, 8, 15, 38	8, 10, 18, 37	10, 36, 37, 40	10, 14, 35, 40	1, 35, 19, 39	28, 27, 18, 40	5, 34, 31, 35		6, 29, 4, 38	19, 1, 32	35, 12, 34, 31	
2	Weight of stationary object		+		10, 1, 29, 35		35, 30, 13, 2		5, 35, 14, 2		8, 10, 19, 35	13, 29, 10, 18	13, 10, 29, 14	26, 39, 1, 40	28, 2, 10, 27		2, 27, 19, 6	28, 19, 32, 22	19, 32, 35		18, 19, 28, 1
3	Length of moving object	8, 15, 29, 34		+		15, 17, 4		7, 17, 4, 35		13, 4, 8	17, 10, 4	1, 8, 35	1, 8, 10, 29	1, 8, 15, 34	8, 35, 29, 34	19		10, 15, 19	32	8, 35, 24	
4	Length of stationary object		35, 28, 40, 29		+		17, 7, 10, 40		35, 8, 2, 14		28, 10	1, 14, 35	13, 14, 15, 7	39, 37, 35	15, 14, 28, 26		1, 10, 35	3, 35, 38, 18	3, 25		
5	Area of moving object	2, 17, 29, 4		14, 15, 18, 4		+		7, 14, 17, 4		29, 30, 4, 34	19, 30, 35, 2	10, 15, 36, 28	5, 34, 29, 4	11, 2, 13, 39	3, 15, 40, 14	6, 3		2, 15, 16	15, 32, 19, 13	19, 32	
6	Area of stationary object		30, 2, 14, 18		26, 7, 9, 39		+				1, 18, 35, 36	10, 15, 36, 37		2, 38	40		2, 10, 19, 30	35, 39, 38			
7	Volume of moving object	2, 26, 29, 40		1, 7, 4, 35		1, 7, 4, 17		+		29, 4, 38, 34	15, 35, 36, 37	6, 35, 36, 37	1, 15, 29, 4	28, 10, 1, 39	9, 14, 15, 7	6, 35, 4		34, 39, 10, 18	2, 13, 10	35	
8	Volume of stationary object		35, 10, 19, 14	19, 14	35, 8, 2, 14				+		2, 18, 37	24, 35	7, 2, 35	34, 28, 35, 40	9, 14, 17, 15		35, 34, 38	35, 6, 4			
9	Speed	2, 28, 13, 38		13, 14, 8		29, 30, 34		7, 29, 34		+	13, 28, 15, 19	6, 18, 38, 40	35, 15, 18, 34	28, 33, 1, 18	8, 3, 26, 14	3, 19, 35, 5		28, 30, 36, 2	10, 13, 19	8, 15, 35, 38	
10	Force (Intensity)	8, 1, 37, 18	18, 13, 1, 28	17, 19, 9, 36	28, 10	19, 10, 15	1, 18, 36, 37	15, 9, 12, 37	2, 36, 18, 37	13, 28, 15, 12	+	18, 21, 11	10, 35, 40, 34	35, 10, 21	35, 10, 14, 27	19, 2		35, 10, 21		19, 17, 10	1, 16, 36, 37
11	Stress or pressure	10, 36, 37, 40	13, 29, 10, 18	35, 10, 36	35, 1, 14, 16	10, 15, 36, 28	10, 15, 36, 37	6, 35, 10	35, 24	6, 35, 36	36, 35, 21	+	35, 4, 15, 10	35, 33, 2, 40	9, 18, 3, 40	19, 3, 27		35, 39, 19, 2		14, 24, 10, 37	
12	Shape	8, 10, 29, 40	15, 10, 26, 3	29, 34, 5, 4	13, 14, 10, 7	5, 34, 4, 10		14, 4, 15, 22	7, 2, 35	35, 15, 34, 18	35, 10, 37, 40	34, 15, 10, 14	+	33, 1, 18, 4	30, 14, 10, 40	14, 26, 9, 25		22, 14, 19, 32	13, 15, 32	2, 6, 34, 14	
13	Stability of the object's composition	21, 35, 2, 39	26, 39, 1, 40	13, 15, 1, 28	37	2, 11, 13	39	28, 10, 19, 39	34, 28, 35, 40	33, 15, 28, 18	10, 35, 21, 16	2, 35, 40	22, 1, 18, 4	+	17, 9, 15	13, 27, 10, 35	39, 3, 35, 23	35, 1, 32	32, 3, 27, 16	13, 19	27, 4, 29, 18
14	Strength	1, 8, 40, 15	40, 26, 27, 1	1, 15, 8, 35	15, 14, 28, 26	3, 34, 40, 29	9, 40, 28	10, 15, 14, 7	9, 14, 17, 15	8, 13, 26, 14	10, 18, 3, 14	10, 3, 18, 40	10, 30, 35, 40	13, 17, 35	+	27, 3, 26		30, 10, 40	35, 19	19, 35, 10	35
15	Duration of action of moving object	19, 5, 34, 31		2, 19, 9		3, 17, 19		10, 2, 19, 30		3, 35, 5	19, 2, 16	19, 3, 27	14, 26, 28, 25	13, 3, 35	27, 3, 10	+		19, 35, 39	2, 19, 4, 35	28, 6, 35, 18	
16	Duration of action by stationary object		6, 27, 19, 16		1, 40, 35				35, 34, 38					39, 3, 35, 23			+	19, 18, 36, 40			
17	Temperature	36, 22, 6, 38	22, 35, 32	15, 19, 9	15, 19, 9	3, 35, 39, 18	35, 38	34, 39, 40, 18	35, 6, 4	2, 28, 36, 30	35, 10, 3, 21	35, 39, 19, 2	14, 22, 19, 32	1, 35, 32	10, 30, 22, 40	19, 13, 39	19, 18, 36, 40	+	32, 30, 21, 16	19, 15, 3, 17	
18	Illumination intensity	19, 1, 32	2, 35, 32	19, 32, 16		19, 32, 26		2, 13, 10		10, 13, 19	26, 19, 6		32, 30	32, 3, 27	35, 19	2, 19, 6		32, 35, 19	+	32, 1, 19	32, 35, 1, 15
19	Use of energy by moving object	12, 18, 28, 31		12, 28		15, 19, 25		35, 13, 18		8, 35, 35	16, 26, 21, 2	23, 14, 25	12, 2, 29	19, 13, 17, 24	5, 19, 9, 35	28, 35, 6, 18	-	19, 24, 3, 14	2, 15, 19	+	-
20	Use of energy by stationary object		19, 9, 6, 27								36, 37			27, 4, 29, 18	35				19, 2, 35, 32	-	+
21	Power	8, 36, 38, 31	19, 26, 17, 27	1, 10, 35, 37		19, 38	17, 32, 13, 38	35, 6, 38	30, 6, 25	15, 35, 2	26, 2, 36, 35	22, 10, 35	29, 14, 2, 40	35, 32, 15, 31	26, 10, 28	19, 35, 10, 38	16	2, 14, 17, 25	16, 6, 19	16, 6, 19, 37	
22	Loss of Energy	15, 6, 19, 28	19, 6, 18, 9	7, 2, 6, 13	6, 38, 7	15, 26, 17, 30	17, 7, 30, 18	7, 18, 23	7	16, 35, 38	36, 38			14, 2, 39, 6	26			19, 38, 7	1, 13, 32, 15		
23	Loss of substance	35, 6, 23, 40	35, 6, 22, 32	14, 29, 10, 39	10, 28, 24	35, 2, 10, 31	10, 18, 39, 31	1, 29, 30, 36	3, 39, 18, 31	10, 13, 28, 38	14, 15, 18, 40	3, 36, 37, 10	29, 35, 3, 5	2, 14, 30, 40	35, 28, 31, 40	28, 27, 3, 18	27, 16, 18, 38	21, 36, 39, 31	1, 6, 13	35, 18, 24, 5	28, 27, 12, 31
24	Loss of Information	10, 24, 35	10, 35, 5	1, 26	26	30, 26	30, 16		2, 22	26, 32						10	10		19		
25	Loss of Time	10, 20, 37, 35	10, 20, 26, 5	15, 2, 29	30, 24, 14, 5	26, 4, 5, 16	10, 35, 17, 4	2, 5, 34, 10	35, 16, 32, 18		10, 37, 36, 5	37, 36, 4	4, 10, 34, 17	35, 3, 22, 5	29, 3, 28, 18	20, 10, 28, 18	28, 20, 10, 16	35, 29, 21, 18	1, 19, 26, 17	35, 38, 19, 18	1
26	Quantity of substance/the matter	35, 6, 18, 31	27, 26, 18, 35	29, 14, 35, 18		15, 14, 29	2, 18, 40, 4	15, 20, 29		35, 29, 34, 28	35, 14, 3	10, 36, 14, 3	35, 14	15, 2, 17, 40	14, 35, 34, 10	3, 35, 10, 40	3, 35, 31	3, 17, 39		34, 29, 16, 18	3, 35, 31
27	Reliability	3, 8, 10, 40	3, 10, 8, 28	15, 9, 14, 4	15, 29, 28, 11	17, 10, 14, 16	32, 35, 40, 4	3, 10, 14, 24	2, 35, 24	21, 35, 11, 28	8, 28, 10, 3	10, 24, 35, 19	35, 1, 16, 11		11, 28	2, 35, 3, 25	34, 27, 6, 40	3, 35, 10	11, 32, 13	21, 11, 27, 19	36, 23
28	Measurement accuracy	32, 35, 26, 28	28, 35, 25, 26	28, 26, 5, 16	32, 28, 3, 16	26, 28, 32, 3	26, 28, 32, 3	32, 13, 6		28, 13, 32, 24	32, 2	6, 28, 32	6, 28, 32	32, 35, 13	28, 6, 32	28, 6, 32	10, 26, 24	6, 19, 28, 24	6, 1, 32	3, 6, 32	
29	Manufacturing precision	28, 32, 13, 18	28, 35, 27, 9	10, 28, 29, 37	2, 32, 10	28, 33, 29, 32	2, 29, 18, 36	32, 23, 2	25, 10, 35	10, 28, 32	28, 19, 34, 36	3, 35	32, 30, 40	30, 18	3, 27	3, 27, 40		19, 26	3, 32	32, 2	
30	Object-affected harmful factors	22, 21, 27, 39	2, 22, 13, 24	17, 1, 39, 4	1, 18	22, 1, 33, 28	27, 2, 39, 35	22, 23, 37, 35	34, 39, 19, 27	21, 22, 35, 28	13, 35, 39, 18	22, 2, 37	22, 1, 3, 35	35, 24, 30, 18	18, 35, 37, 1	22, 15, 33, 28	17, 1, 40, 33	22, 33, 35, 2	1, 19, 32, 13	1, 24, 6, 27	10, 2, 22, 37
31	Object-generated harmful factors	19, 22, 15, 39	35, 22, 1, 39	17, 15, 16, 22		17, 2, 18, 39	22, 1, 40	17, 2, 40	30, 18, 35, 4	35, 28, 3, 23	35, 28, 1, 40	2, 33, 27, 18	35, 1	35, 40, 27, 39	15, 35, 22, 2	15, 22, 33, 31	21, 39, 16, 22	22, 35, 2, 24	19, 24, 39, 32	2, 35, 6	19, 22, 18
32	Ease of manufacture	28, 29, 15, 16	1, 27, 36, 13	1, 29, 13, 17	15, 17, 27	13, 1, 26, 12	16, 40	13, 29, 1, 40	35	35, 13, 8, 1	35, 12	35, 19, 1, 37	1, 28, 13, 27	11, 13, 1	1, 3, 10, 32	27, 1, 4	35, 16	27, 26, 18	28, 24, 27, 1	28, 26, 27, 1	1, 4
33	Ease of operation	25, 2, 13, 15	6, 13, 1, 25	1, 17, 13, 12		1, 17, 13, 16	18, 16, 15, 39	1, 16, 35, 15	4, 18, 39, 31	18, 13, 34	28, 13, 35	2, 32, 12	15, 34, 29, 28	32, 35, 30	32, 40, 3, 28	29, 3, 8, 25	1, 16, 25	26, 27, 13	13, 17, 1, 24	1, 13, 24	
34	Ease of repair	2, 27, 35, 11	2, 27, 35, 11	1, 28, 10, 25	3, 18, 31	15, 13, 32	16, 25	25, 2, 35, 11	1	34, 9	1, 11, 10	13	1, 13, 2, 4	2, 35	11, 1, 2, 9	11, 29, 28, 27	1	4, 10	15, 1, 13	15, 1, 28, 16	
35	Adaptability or versatility	1, 6, 15, 8	19, 15, 29, 16	35, 1, 29, 2	1, 35, 16	35, 30, 29, 7	15, 16	15, 35, 29		35, 10, 14	15, 17, 20	35, 16	15, 37, 1, 8	35, 30, 14	35, 3, 32, 6	13, 1, 35	2, 16	27, 2, 3, 35	6, 22, 26, 1	19, 35, 29, 13	
36	Device complexity	26, 30, 34, 36	2, 26, 35, 39	1, 19, 26, 24	26	14, 1, 13, 16	6, 36	34, 26, 6	1, 16	34, 10, 28	26, 16	19, 1, 35	29, 13, 28, 15	2, 22, 17, 19	2, 13, 28	10, 4, 28, 15		2, 17, 13	24, 17, 13	27, 2, 29, 28	
37	Difficulty of detecting and measuring	27, 26, 28, 13	6, 13, 28, 1	16, 17, 26, 24	26	2, 13, 18, 17	2, 39, 30, 16	29, 1, 4, 16	2, 18, 26, 31	3, 4, 16, 35	30, 28, 40, 19	35, 36, 37, 32	27, 13, 1, 39	11, 22, 39, 30	27, 3, 15, 28	19, 29, 39, 25	25, 34, 6, 35	3, 27, 35, 16	2, 24, 26	35, 38	19, 35, 16
38	Extent of automation	28, 26, 18, 35	28, 26, 35, 10	14, 13, 17, 28	23	17, 14, 13		35, 13, 16		28, 10	2, 35	13, 35	15, 32, 1, 13	18, 1	25, 13	6, 9		26, 2, 19	8, 32, 19	2, 32, 13	
39	Productivity	35, 26, 24, 37	28, 27, 15, 3	18, 4, 28, 38	30, 7, 14, 26	10, 26, 34, 31	10, 35, 17, 7	2, 6, 34, 10	35, 37, 10, 2		28, 15, 10, 36	10, 37, 14	14, 10, 34, 40	35, 3, 22, 39	29, 28, 10, 18	35, 10, 2, 18	20, 10, 16, 38	35, 21, 28, 10	26, 17, 19, 1	35, 10, 38, 19	1

	Improving Feature	21 Power	22 Loss of Energy	23 Loss of Substance	24 Loss of Information	25 Loss of Time	26 Quantity of substance	27 Reliability	28 Measurement accuracy	29 Manufacturing precision	30 Object-affected harmful factors	31 Object-generated harmful factors	32 Ease of manufacture	33 Ease of operation	34 Ease of repair	35 Adaptability or versatility	36 Device complexity	37 Difficulty of detecting and measuring	38 Extent of automation	39 Productivity
1	Weight of moving object	12, 36, 18, 31	6, 2, 34, 19	5, 35, 3, 31	10, 24, 35	10, 35, 20, 28	3, 26, 18, 31	1, 3, 11, 27	28, 27, 35, 26	28, 35, 26, 18	22, 21, 18, 27	22, 35, 31, 39	27, 28, 1, 36	35, 3, 2, 24	2, 27, 28, 11	29, 5, 15, 8	26, 30, 36, 34	28, 29, 26, 32	26, 35, 18, 19	35, 3, 24, 37
2	Weight of stationary object	15, 19, 18, 22	18, 19, 28, 15	5, 8, 13, 30	10, 15, 35	10, 20, 35, 26	19, 6, 18, 26	10, 28, 8, 3	18, 26, 28	10, 1, 35, 17	2, 19, 22, 37	35, 22, 1, 39	28, 1, 9	6, 13, 1, 32	2, 27, 28, 11	19, 15, 29	1, 10, 26, 39	25, 28, 17, 15	2, 26, 35	1, 28, 15, 35
3	Length of moving object	1, 35	7, 2, 35, 39	4, 29, 23, 10	1, 24	15, 2, 29	29, 35	10, 14, 29, 40	28, 32, 4	10, 28, 29, 37	1, 15, 17, 24	17, 15	1, 29, 17	15, 29, 35, 4	1, 28, 10	14, 15, 1, 16	1, 19, 26, 24	35, 1, 26, 24	17, 24, 26, 16	14, 4, 28, 29
4	Length of stationary object	12, 8	6, 28	10, 28, 24, 35	24, 26	30, 29, 14		15, 29, 28	32, 28, 3	2, 32, 10	1, 18		15, 17, 27	2, 25	3	1, 35	1, 26	26		30, 14, 7, 26
5	Area of moving object	19, 10, 32, 18	15, 17, 30, 26	10, 35, 2, 39	30, 26	26, 4	29, 30, 6, 13	29, 9	26, 28, 32, 3	2, 32	22, 33, 28, 1	17, 2, 18, 39	13, 1, 26, 24	15, 17, 13, 16	15, 13, 10, 1	15, 30	14, 1, 13	2, 36, 26, 18	14, 30, 28, 23	10, 26, 34, 2
6	Area of stationary object	17, 32	17, 7, 30	10, 14, 18, 39	30, 16	10, 35, 4, 18	2, 18, 40, 4	32, 35, 40, 4	26, 28, 32, 3	2, 29, 18, 36	27, 2, 39, 35	22, 1, 40	40, 16	16, 4	16	15, 16	1, 18, 36	2, 35, 30, 18	23	10, 15, 17, 7
7	Volume of moving object	35, 6, 13, 18	7, 15, 13, 16	36, 39, 34, 10	2, 22	2, 6, 34, 10	29, 30, 7	14, 1, 40, 11	25, 26, 28	25, 28, 2, 16	22, 21, 27, 35	17, 2, 40, 1	29, 1, 40	15, 13, 30, 12	10	15, 29	26, 1	29, 26, 4	35, 34, 16, 24	10, 6, 2, 34
8	Volume of stationary object	30, 6		10, 39, 35, 34		35, 16, 32, 18	35, 3	2, 35, 16		35, 10, 25	34, 39, 19, 27	30, 18, 35, 4	35		1		1, 31	2, 17, 26		35, 37, 10, 2
9	Speed	19, 35, 38, 2	14, 20, 19, 35	10, 13, 28, 38	13, 26		10, 19, 29, 38	11, 35, 27, 28	28, 32, 1, 24	10, 28, 32, 25	1, 28, 35, 23	2, 24, 35, 21	35, 13, 8, 1	32, 28, 13, 12	34, 2, 28, 27	15, 10, 26	10, 28, 4, 34	3, 34, 27, 16	10, 18	
10	Force (Intensity)	19, 35, 18, 37	14, 15	8, 35, 40, 5		10, 37, 36	14, 29, 18, 36	3, 35, 13, 21	35, 10, 23, 24	28, 29, 37, 36	1, 35, 40, 18	13, 3, 36, 24	15, 37, 18, 1	1, 28, 3, 25	15, 1, 11	15, 17, 18, 20	26, 35, 10, 18	36, 37, 10, 19	2, 35	3, 28, 35, 37
11	Stress or pressure	10, 35, 14	2, 36, 25	10, 36, 3, 37		37, 36, 4	10, 14, 36	10, 13, 19, 35	6, 28, 25	3, 35	22, 2, 37	2, 33, 27, 18	1, 35, 16	11	2	35	19, 1, 35	2, 36, 37	35, 24	10, 14, 35, 37
12	Shape	4, 6, 2	14	35, 29, 3, 5		14, 10, 34, 17	36, 22	10, 40, 16	28, 32, 1	32, 30, 40	22, 1, 2, 35	35, 1	1, 32, 17, 28	32, 15, 26	2, 13, 1	1, 15, 29	16, 29, 1, 28	15, 13, 39	15, 1, 32	17, 26, 34, 10
13	Stability of the object's composition	32, 35, 27, 31	14, 2, 39, 6	2, 14, 30, 40		35, 27	15, 32, 35		13	18	35, 24, 30, 18	35, 40, 27, 39	35, 19	32, 35, 30	2, 35, 10, 16	35, 30, 34, 2	2, 35, 22, 26	35, 22, 39, 23	1, 8, 35	23, 35, 40, 3
14	Strength	10, 26, 35, 28	35	35, 28, 31, 40		29, 3, 28, 10	29, 10, 27	11, 3	3, 27, 16	3, 27	18, 35, 37, 1	15, 35, 22, 2	11, 3, 10, 32	32, 40, 25, 2	27, 11, 3	15, 3, 32	2, 13, 25, 28	27, 3, 15, 40	15	29, 35, 10, 14
15	Duration of action of moving object	19, 10, 35, 38		28, 27, 3, 18	10	20, 10, 28, 18	3, 35, 10, 40	11, 2, 13	3	3, 27, 16, 40	22, 15, 33, 28	21, 39, 16, 22	27, 1, 4	12, 27	29, 10, 27	1, 35, 13	10, 4, 29, 15	19, 29, 39, 35	6, 10	35, 17, 14, 19
16	Duration of action by stationary object	16		27, 16, 18, 38	10	28, 20, 10, 16	3, 35, 31	34, 27, 6, 40	10, 26, 24		17, 1, 40, 33	22	35, 10	1	1	2		25, 34, 6, 35	1	20, 10, 16, 38
17	Temperature	2, 14, 17, 25	21, 17, 35, 38	21, 36, 29, 31		35, 28, 21, 18	3, 17, 30, 39	19, 35, 3, 10	32, 19, 24	24	22, 33, 35, 2	22, 35, 2, 24	26, 27	26, 27	4, 10, 16	2, 18, 27	2, 17, 16	3, 27, 35, 31	26, 2, 19, 16	15, 28, 35
18	Illumination intensity	32	13, 16, 1, 6	13, 1	1, 6	19, 1, 26, 17	1, 19		11, 15, 32	3, 32	15, 19	35, 19, 32, 39	19, 35, 28, 26	28, 26, 19	15, 17, 13, 16	15, 1, 19	6, 32, 13	32, 15	2, 26, 10	2, 25, 16
19	Use of energy by moving object	6, 19, 37, 18	12, 22, 15, 24	35, 24, 18, 5		35, 38, 19, 18	34, 23, 16, 18	19, 21, 11, 27	3, 1, 32		1, 35, 6, 27	2, 35, 6	28, 26, 30	19, 35	1, 15, 17, 28	15, 17, 13, 16	2, 29, 27, 28	35, 38	32, 2	12, 28, 35
20	Use of energy by stationary object			28, 27, 18, 31			3, 35, 31	10, 36, 23			10, 2, 22, 37	19, 22, 18	1, 4					19, 35, 16, 25		1, 6
21	Power	+	10, 35, 38	28, 27, 18, 38	10, 19	35, 20, 10, 6	4, 34, 19	19, 24, 26, 31	32, 15, 2	32, 2	19, 22, 31, 2	2, 35, 18	26, 10, 34	26, 35, 10	35, 2, 10, 34	19, 17, 34	20, 19, 30, 34	19, 35, 16	28, 2, 17	28, 35, 34
22	Loss of Energy	3, 38	+	35, 27, 2, 37	19, 10	10, 18, 32, 7	7, 18, 25	11, 10, 35	32		21, 22, 35, 2	21, 35, 2, 22		35, 32, 1	2, 19		7, 23	35, 3, 15, 23	2	28, 10, 29, 35
23	Loss of substance	28, 27, 18, 38	35, 27, 2, 31	+		15, 18, 35, 10	6, 3, 10, 24	10, 29, 39, 35	16, 34, 31, 28	35, 10, 24, 31	33, 22, 30, 40	10, 1, 34, 29	15, 34, 33	32, 28, 2, 24	2, 35, 34, 27	15, 10, 2	35, 10, 28, 24	35, 18, 10, 13	35, 10, 18	28, 35, 10, 23
24	Loss of Information	10, 19	19, 10		+	24, 26, 28, 32	24, 28, 35	10, 28, 23			22, 10, 1	10, 21, 22	32	27, 22				35, 33	35	13, 23, 15
25	Loss of Time	35, 20, 10, 6	10, 5, 18, 32	35, 18, 10, 39	24, 26, 28, 32	+	35, 38, 18, 16	10, 30, 4	24, 34, 28, 32	24, 26, 28, 18	35, 18, 34	35, 22, 18, 39	35, 28, 34, 4	4, 28, 10, 34	32, 1, 10	35, 28	6, 29	18, 28, 32, 10	24, 28, 35, 30	
26	Quantity of substance/the matter	35	7, 18, 25	6, 3, 10, 24	24, 28, 35	35, 38, 18, 16	+	18, 3, 28, 40	13, 2, 28	33, 30	35, 33, 29, 31	3, 35, 40, 39	29, 1, 35, 27	35, 29, 25, 10	2, 32, 10, 25	15, 3, 29	3, 13, 27, 10	3, 27, 29, 18	8, 35	13, 29, 3, 27
27	Reliability	21, 11, 26, 31	10, 11, 35	10, 35, 29, 39	10, 28	10, 30, 4	21, 28, 40, 3	+	32, 3, 11, 23	11, 32, 1	27, 35, 2, 40	35, 2, 40, 26		27, 17, 40	1, 11	13, 35, 8, 24	13, 35, 1	27, 40, 28	11, 13, 27	1, 35, 29, 38
28	Measurement accuracy	3, 6, 32	26, 32, 27	10, 16, 31, 28		24, 34, 28, 32	2, 6, 32	5, 11, 1, 23	+		28, 24, 22, 26	3, 33, 39, 10	6, 35, 25, 18	1, 13, 17, 34	1, 32, 13, 11	13, 35, 2	27, 35, 10, 34	26, 24, 32, 28	28, 2, 10, 34	10, 34, 28, 32
29	Manufacturing precision	32, 2	13, 32, 2	35, 31, 10, 24		32, 26, 28, 18	32, 30	11, 32, 1		+	26, 28, 10, 36	4, 17, 34, 26		1, 32, 35, 23	25, 10		26, 2, 18		26, 28, 18, 23	10, 18, 32, 39
30	Object-affected harmful factors	19, 22, 31, 2	21, 22, 35, 2	33, 22, 19, 40	22, 10, 2	35, 18, 34	35, 33, 29, 31	27, 24, 2, 40	28, 33, 23, 26	26, 28, 10, 18	+		24, 35, 2	2, 25, 28, 39	35, 10, 2	35, 11, 22, 31	22, 19, 29, 40	22, 19, 29, 40	33, 3, 34	22, 35, 13, 24
31	Object-generated harmful factors	2, 35, 18	21, 35, 2, 22	10, 1, 34	10, 21, 29	1, 22	3, 24, 39, 1	24, 2, 40, 39	3, 33, 26	4, 17, 34, 26		+					19, 1, 31	2, 21, 27, 1	2	22, 35, 18, 39
32	Ease of manufacture	27, 1, 12, 24	19, 35	15, 34, 33	32, 24, 18, 16	35, 28, 34, 4	35, 23, 1, 24		1, 35, 12, 18		24, 2		+	2, 5, 13, 16	35, 1, 11, 9	2, 13, 15	27, 26, 1	6, 28, 11, 1	8, 28, 1	35, 1, 10, 28
33	Ease of operation	35, 34, 2, 10	2, 19, 13	28, 32, 2, 24	4, 10, 27, 22	4, 28, 10, 34	12, 35	17, 27, 8, 40	25, 13, 2, 34	1, 32, 35, 23	2, 25, 28, 39		2, 5, 12	+	12, 26, 1, 32	15, 34, 1, 16	32, 26, 12, 17		1, 34, 12, 3	15, 1, 28
34	Ease of repair	15, 10, 32, 2	15, 1, 32, 19	2, 35, 34, 27		32, 1, 10, 25	2, 28, 10, 25	11, 10, 1, 16	10, 2, 13	25, 10	35, 10, 2, 16		1, 35, 11, 10	1, 12, 26, 15	+	7, 1, 4, 16	35, 1, 13, 11		34, 35, 7, 13	1, 32, 10
35	Adaptability or versatility	19, 1, 29	18, 15, 1	15, 10, 2, 13		35, 28	3, 35, 15	35, 13, 8, 24	35, 5, 1, 10		35, 11, 32, 31		1, 13, 31	15, 34, 1, 16	1, 16, 7, 4	+	15, 29, 37, 28	1	27, 34, 35	35, 28, 6, 37
36	Device complexity	20, 19, 30, 34	10, 35, 13, 2	35, 10, 28, 29		6, 29	13, 3, 27, 10	13, 35, 1	2, 26, 10, 34	26, 24, 32	22, 19, 29, 40	19, 1	27, 26, 1, 13	27, 9, 26, 24	1, 13	29, 15, 28, 37	+	15, 10, 37, 28	15, 1, 24	12, 17, 28
37	Difficulty of detecting and measuring	18, 1, 16, 10	35, 3, 15, 19	1, 18, 10, 24	35, 33, 27, 22	18, 28, 32, 9	3, 27, 29, 18	27, 40, 28, 8	26, 24, 32, 28		22, 19, 29, 28	2, 21	5, 28, 11, 29	2, 5	12, 26	1, 15	15, 10, 37, 28	+	34, 21	35, 18
38	Extent of automation	28, 2, 27	23, 28	35, 10, 18, 5	35, 33	24, 28, 35, 30	35, 13	11, 27, 32	28, 26, 10, 34	28, 26, 18, 23	2, 33	2	1, 26, 13	1, 12, 34, 3	1, 35, 13	27, 4, 1, 35	15, 24, 10	34, 27, 25	+	5, 12, 35, 26
39	Productivity	35, 20, 10	28, 10, 29, 35	28, 10, 35, 23	13, 15, 23		35, 38	1, 35, 10, 38	1, 10, 34, 28	18, 10, 32, 1	22, 35, 13, 24	35, 22, 18, 39	35, 28, 2, 24	1, 28, 7, 10	1, 32, 10, 25	1, 35, 28, 37	12, 17, 28, 24	35, 18, 27, 2	5, 12, 35, 26	+

Appendix B: EEC and WBSCD Category Comparison

Environmental Engineering Characteristics Categories

Attempts were made to create categories that reflect the product design process in order to better organize the TRIZ database for environmental design. Recall that the WBCSD and Eco-Compass categories were based on environmental impact of the product life cycle and were similar in structure Chapter 2.2 [13, 18]. Liu and Chen sorted the 39 TRIZ engineering characteristics with respect to the WBCSD categories [19]. This section outlines attempts to create environmental categories based on decision making during the product design process.

TRIZ is a concept generation tool that is applied early in the design process therefore the early decision outcomes will influence the environmental scores of a finished product. These categories represent the areas of product development, function and life cycle that an engineer would be considering during concept generation. The categories are as follows:

- Product Creation (Manufacturing)
- Lifetime
- Material Inputs
- Outputs
- Efficiency
- Energy Usage

The EECs are sorted into these categories in Table 6. Product Creation represents environmental areas for improvement of the manufacturing process. The Lifetime category contains EECs that would relate to the overall lifecycle of the product after manufacturing: the longer a product performs, the less waste is created and less material is used to replace it. Material Inputs is not the amount of material that goes into making the part, rather it is any form of fuel or substance that is used by the product during the life cycle. This would include human interaction, maintenance, and material energy input (such as coal, wood, person.). Conversely, the Outputs are any substance or energy that exits the product, including light, heat, energy and material. The Efficiency category refers to the reducing the amount of energy that is not applied directly to the intended function. The sixth and final category focuses on Energy Usage. The less energy that a product uses, the more environmentally benign it is, and that assertion is the underlying principle that is considered in ENERGY STAR products. A comparison of the PDP and WBCSD categories is provided in Figure 29.

Table 6: PDP Category matrix that shows the categories to which each EEC belongs

		Product Creation	Lifetime	Material Inputs	Outputs	Efficiency	Energy Usage
15	Durability of moving object		x				
16	Durability of non-moving object		x				
17	Temperature				x		x
18	Brightness				x		x
19	Energy spent by moving object			x		x	x
20	Energy spent by non-moving object			x		x	x
21	Power					x	x
22	Waste of energy				x	x	x
23	Waste of substance	x			x	x	
24	Loss of information				x	x	
25	Waste of time					x	
26	Amount of substance	x		x	x		x
27	Reliability		x			x	
28	Accuracy of measurement				x	x	x
29	Accuracy of manufacturing	x	x			x	
30	Harmful factors acting on object		x	x			
31	Harmful side effects	x			x		
32	Manufacturability	x					
33	Convenience of use		x	x	x	x	x
34	Repairability	x	x	x		x	
35	Adaptability		x			x	
36	Complexity of device	x					
37	Complexity of control			x			
38	Level of automation	x					
39	Productivity	x				x	

Each decision made during the design process will change the eventual outcome of the product. Since the WBCSD categories are based primarily on the product performance, it stands to reason that there are multiple points during the design process that would have influence. For this reason, the comparison in Figure 29 appears chaotic. Decisions are made during the PDP regarding material inputs, energy usage, product creation, lifetime and outputs that will all influence the renewable resources of the end product. The 39 ECs were sorted into the PDP categories and a side-by-side comparison was conducted with the work from Liu and Chen, shown in Table 7. Further research would need to be conducted to ascertain the extent of the similarities. Categorizing the TRIZ engineering characteristics in this manner could lead to a new method of searching for analogous solutions.

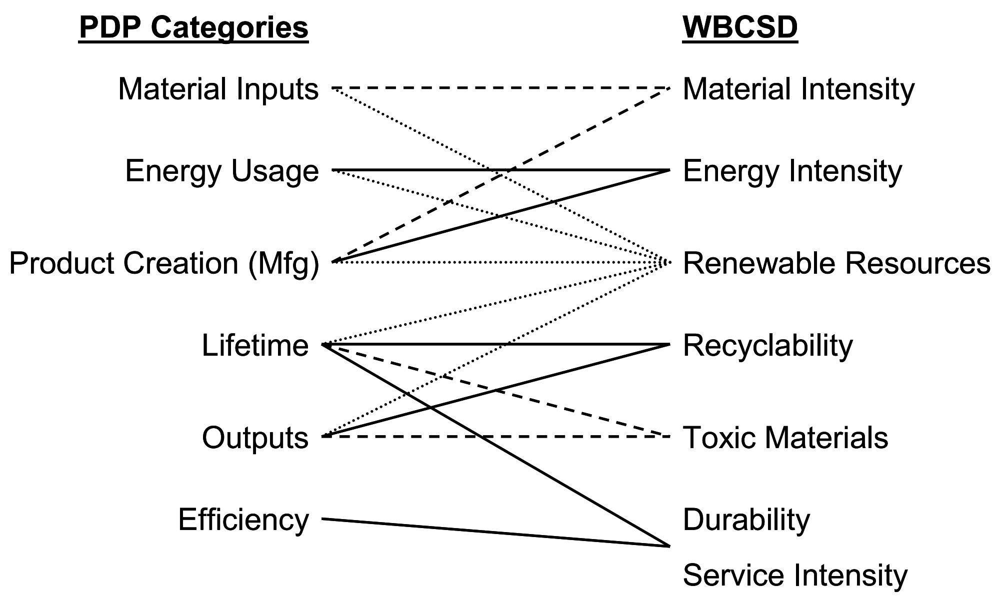


Figure 29: Comparison of PDP and WBCSD Categories

Table 7: Comparison Matrix of Environmental Categories Proposed and WBSCD [18, 19]

		PDP Cateogries						WBCSD Categories						
TRIZ Ecs		Product Creation	Lifetime	Material Usage	Outputs	Efficiency	Energy Usage	Material Intensity	Energy Intensity	Toxic Material	Recyclability	Renewable Resources	Durability	Service Intensity
1	Weight of Mobile Object	x		x			x	x	x					
2	Weight of Stationary Object	x		x				x						
3	Length of Mobile Object	x		x			x	x	x					
4	Length of Stationary Object	x		x				x						
5	Area of Mobile Object	x		x			x	x	x					
6	Area of Stationary Object	x		x				x						
7	Volume of Mobile Object	x		x			x	x	x					
8	Volume of Stationary Object	x		x				x						
9	Rate of Change, Speed		x		x	x	x				x			x
10	Force Exerted by Object		x		x	x	x				x			
11	Stress, Pressure Exerted upon Object		x				x				x			
12	Shape of Object	x		x				x						
13	Stability of Object's Composition	x				x				x			x	
14	Strength of Object	x		x				x				x	x	
15	Durability of moving object		x										x	
16	Durability of non-moving object		x										x	
17	Temperature				x		x		x					
18	Brightness				x		x		x					
19	Energy spent by moving object			x		x	x		x					
20	Energy spent by non-moving object			x		x	x		x					
21	Power					x	x		x					
22	Waste of energy				x	x	x		x					
23	Waste of substance	x			x	x		x						
24	Loss of information				x	x								x
25	Waste of time					x								x
26	Amount of substance	x		x	x			x						
27	Reliability		x			x								x
28	Accuracy of measurement				x	x	x				x			
29	Accuracy of manufacturing	x	x			x					x			
30	Harmful factors acting on object		x	x								x	x	
31	Harmful side effects	x			x					x				
32	Manufacturability	x						x	x		x			
33	Convenience of use		x	x	x	x	x							x
34	Repairability	x	x	x		x						x	x	
35	Adaptability		x	x		x								x
36	Complexity of device	x		x							x			
37	Complexity of control			x										x
38	Level of automation	x												x
39	Productivity	x				x		x	x					x

Appendix C: Function Models

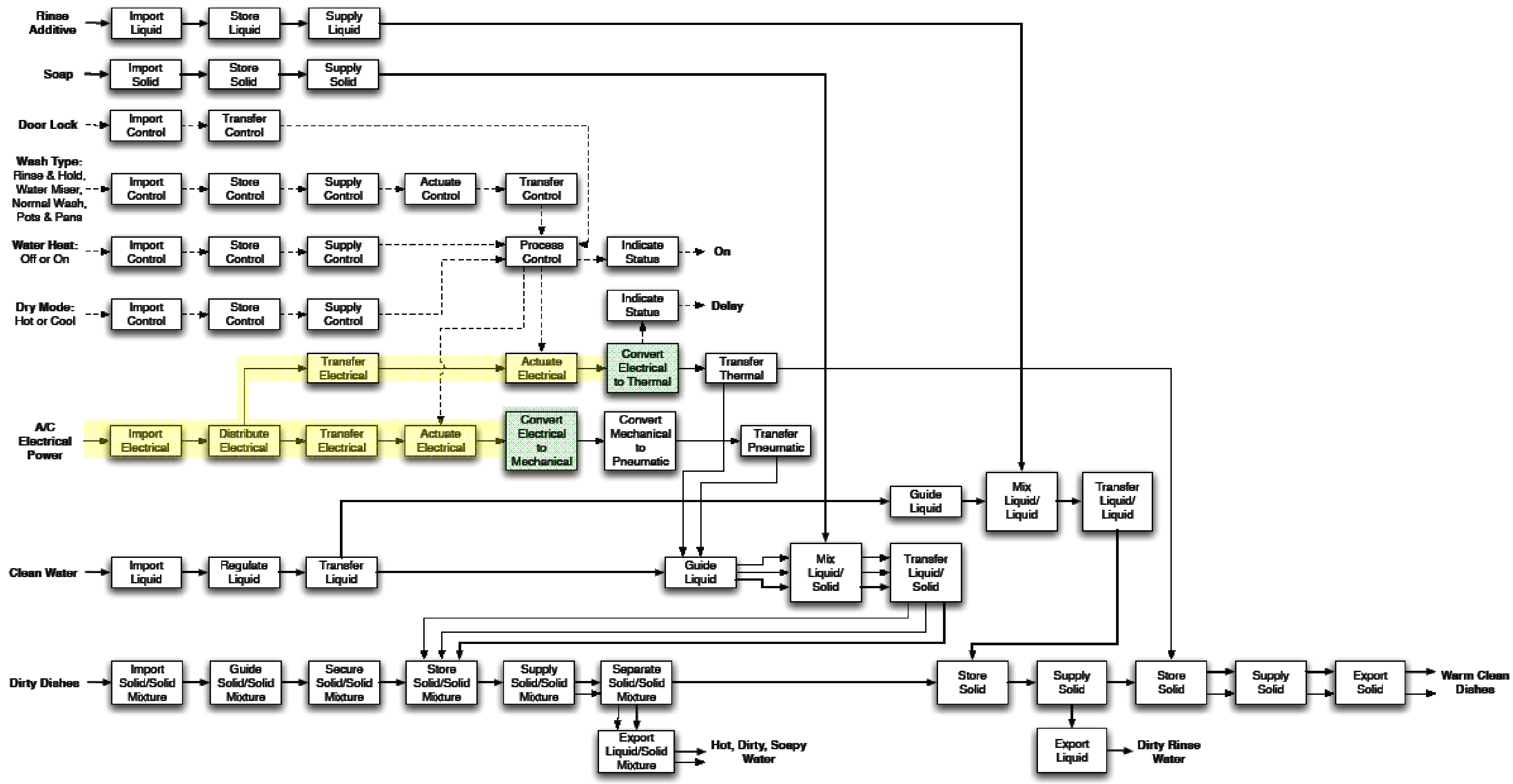


Figure 30: Functional model of a household dishwasher [24]. Electrical energy flows and classes are highlighted.

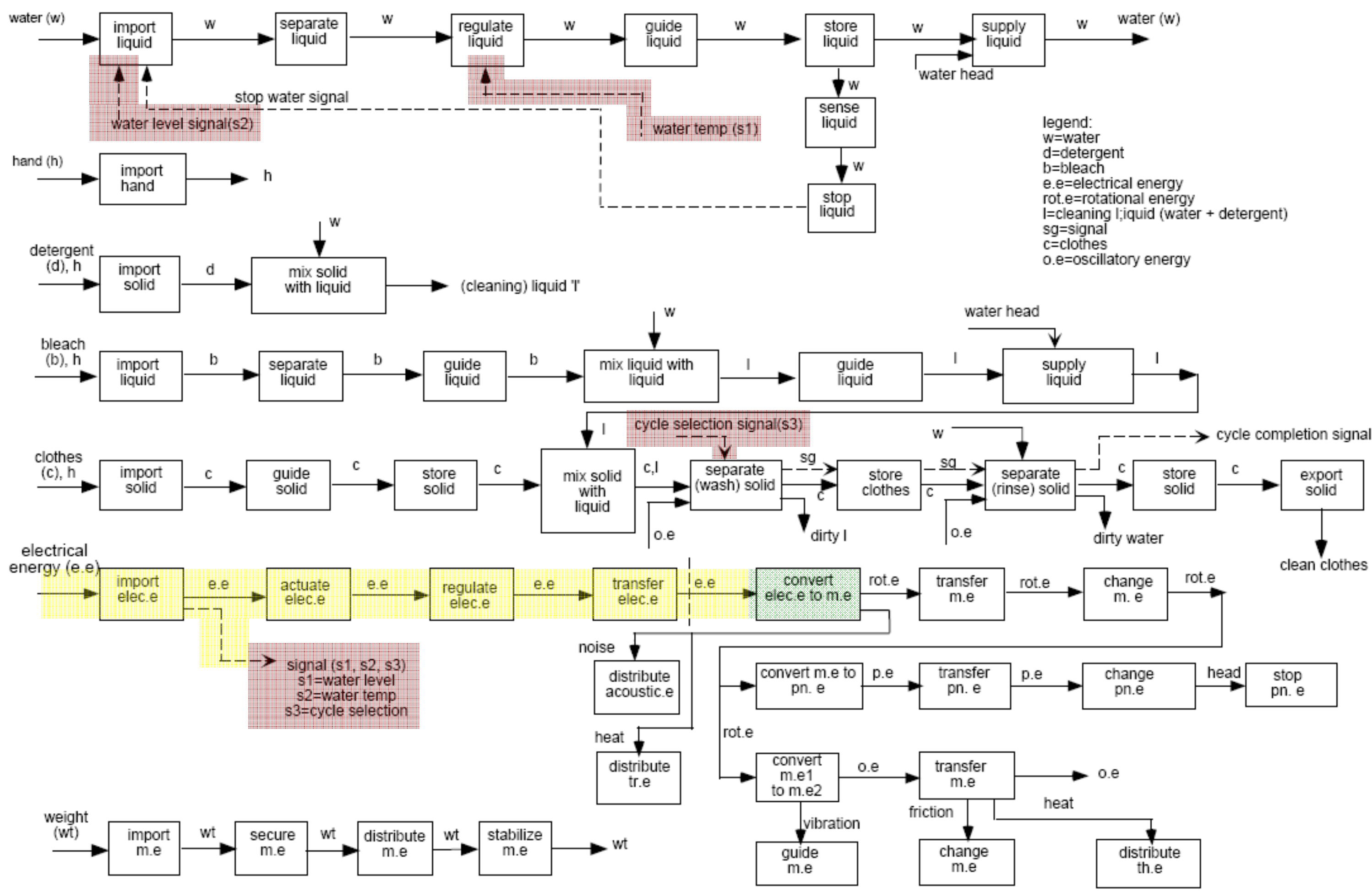


Figure 31: Functional model of a household clothes washer [24]. Electrical energy flows, signals and classes are highlighted.

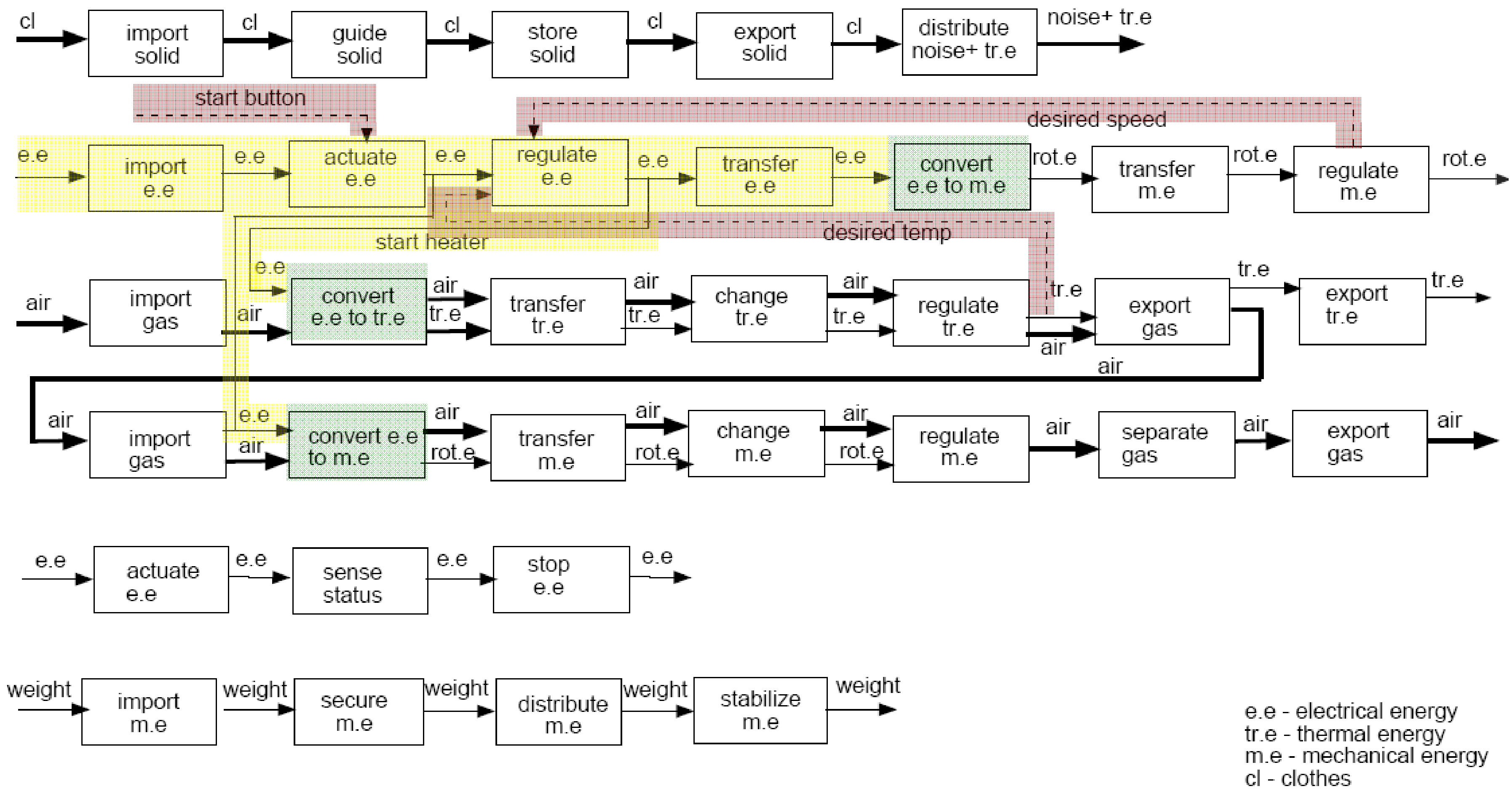


Figure 32: Functional model of a household clothes dryer [24]. Electrical energy flows, signals and classes are highlighted.

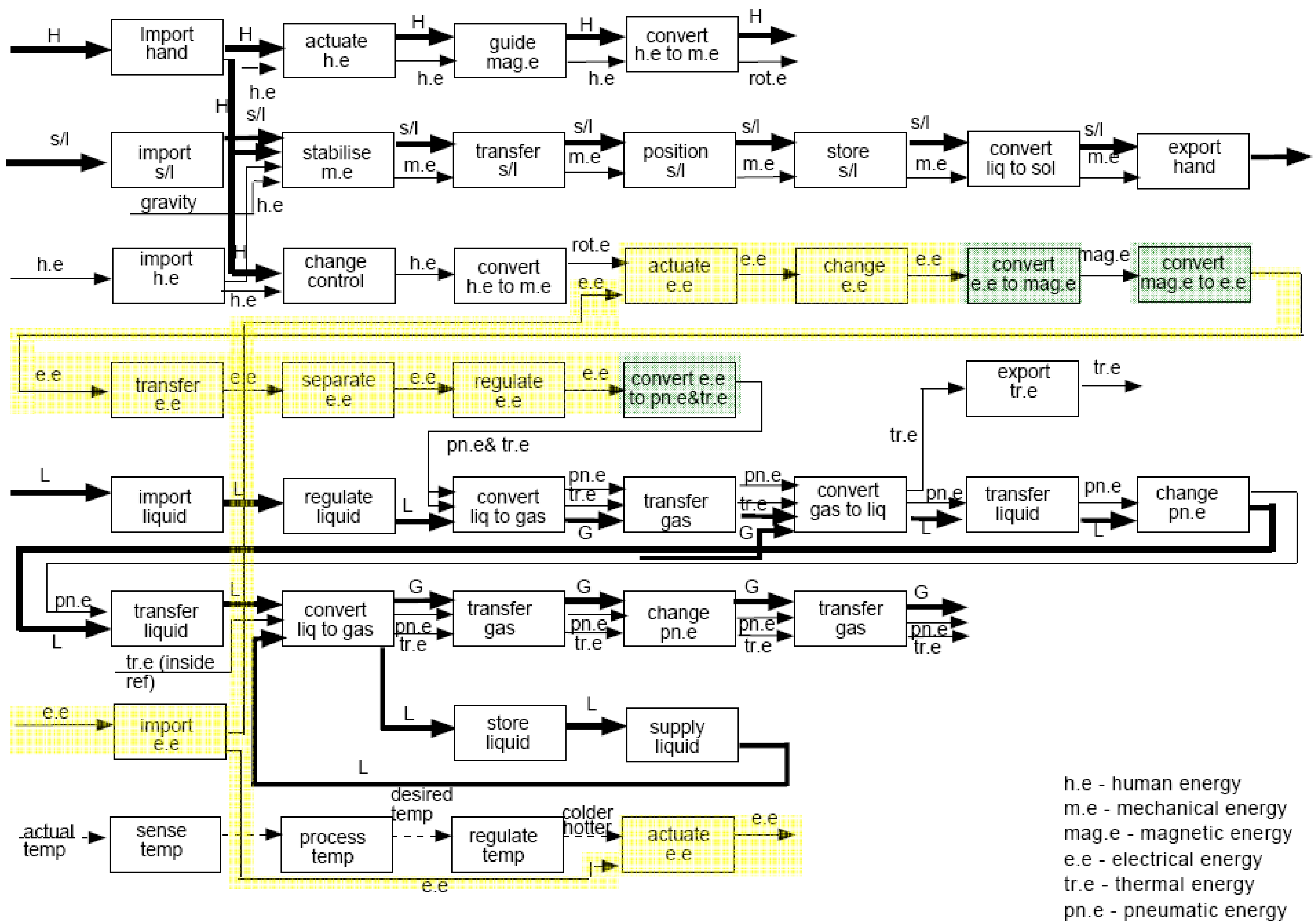


Figure 33: Functional model of a household refrigerator [24]. Electrical energy flows and classes are highlighted.

Appendix D: Additional Information for ENERGY STAR Database [2]

Table 8: ENERGY STAR Metrics for Room Air Conditioners

Room Air Conditioners				
Capacity (BTU/hour)	**Federal Standard EER[1] (with louvered sides)**	**Energy Start EER[1] (with louvered sides)**	**Federal Standard EER[1] (without louvered sides)**	**Energy Star EER[1] (without louvered sides)**
< 6,000	≥ 9.7	≥ 10.7	≥ 9.0	≥ 9.9
6,000 to 7,999				
8,000 to 13,999	≥ 9.8	≥ 10.8	≥ 8.5	≥ 9.4
14,000 to 19,999	≥ 9.7	≥ 10.7		
≥ 20,000	≥ 8.5	≥ 9.4		
Casement	**Federal Standard EER**		**Energy Star EER**	
Casement-Only	≥ 8.5		≥ 9.6	
Casement-Slider	≥ 9.5		≥ 10.5	
Reverse Cycle[2]				
Capacity (BTU/hour)	**Federal Standard EER (with louvered sides)**	**Energy Start EER (with louvered sides)**	**Federal Standard EER (without louvered sides)**	**Energy Star EER (without louvered sides)**
< 14,000			≥ 8.5	≥ 9.4
≥ 14,000			≥ 8.0	≥ 8.8
< 20,000	≥ 9.0	≥ 9.9		
≥ 20,000	≥ 8.5	≥ 9.4		

[1]**Energy Efficiency Ratio (EER)**: This is the ratio of the cooling effect measured in BTU per hour divided by the electrical energy input in measured Watts. The EER must exceed the corresponding 2000 NAECA standard by 10%.

[2]**Reverse Cycle**: Refers to the heating function found in certain room air conditioner models.

RAC: Room air conditioner.

TTW: Room air conditioner units without louvered sides are also referred to as "through the wall" units. TTW is the acronym of this term. These units may also be referred to as "built-in" units.

Casement-only: Refers to a RAC designed for mounting in a casement window with an encased assembly with a width of 14.8 inches or less and a height of 11.2 inches or less.

Casement-slider: Refers to a RAC with an encased assembly designed for mounting in a sliding or casement window with a width of 15.5 inches or less.

PTAC: The acronym for packaged terminal air conditioner. PTACs include self-contained air conditioning units and may connect to an external heating system or may include electrical resistance heating. PTACs are not covered under NAECA's RAC product classes. EPACT mandates that ASHRAE Standard 90.1-2001 govern PTAC energy performance.

Table 9: ENERGY STAR Metrics for Dehumidifiers

Dehumidifiers	
Product Capacity[2] (pints/day)	**EF[1] Under Test Conditions (L/kWh)**
≤ 25	≥ 1.20
> 25 to ≤ 35	≥ 1.40
> 35 to ≤ 45	≥ 1.50
> 45 to ≤ 54	≥ 1.60
> 54 to ≤ 75	≥ 1.60
> 54 to ≤ 75	≥ 1.80
> 75 to ≤ 185	≥ 2.50

Dehumidifier: a self-contained, electrically operated, and mechanically refrigerated encased assembly consisting of:

(a) A refrigerated surface (evaporator) that condenses moisture from the atmosphere;

(b) A refrigerating system, including an electric motor;

(c) An air-circulating fan; and

(d) Means for collecting and/or disposing of the condensate.

[1]**Energy Factor**: Liters of water removed per kilowatt-hour (kWh) of energy consumed or L/kWh. In general, a higher energy factor means a more efficient dehumidifier.

[2]**Capacity**: Measured in pints per 24 hours and is determined by the size of the space and the conditions that exist in the space before dehumidification.

Standard Capacity Dehumidifiers: Dehumidifiers with daily water-removal capacities up to 75.0 US pints (35.5 Liters).

High Capacity Dehumidifiers: Dehumidifiers with daily water-removal capacities from 75.0 US pints up to 185 US pints (87.5 Liters).

Table 10: ENERGY STAR Metrics for Clothes Washers

Clothes Washers	
Energy Star Criteria	$MEF^1 \geq 1.72$
	$WF^2 \leq 8.0$
Federal Criteria	$MEF^1 \geq 1.26$

Qualifying Clothes Washers: The current DOE federal standard (NAECA) for clothes washers includes five product classes:
i) Top-loading < 1.6 ft^3 (compact)
ii) Top-loading > 1.6 ft^3 (standard)
iii) Top-loading/semi automatic
iv) Front-loading
v) Suds-saving

Only standard-sized (> 1.6ft^3), front- or top-loading clothes washers are eligible for the ENERGY STAR clothes washer program.

[1]**Modified Energy Factor (MEF)**: The present energy efficiency measure for all clothes washers. MEF is the quotient of the cubic foot capacity of the clothes container divided by the total clothes washer energy consumption per cycle, with such energy consumption expressed as the sum of the machine electrical energy consumption, the hot water energy consumption, and the energy required for removal of the remaining moisture in the wash load. The units are cubic feet per kWh per cycle (ft^3/kWh/cycle). Clothes washers with higher MEF values are more efficient.

[2]**Water Factor (WF)**: The present water efficiency calculation that allows the comparison of clothes washer water consumption independent of clothes washer capacity. The term is expressed as gallons per cycle per cubic feet. WF is the quotient of the total weighted per-cycle water consumption divided by the capacity of the clothes washer. A clothes washer with a lower water factor is more efficient. WF has not been incorporated into the Federal standard but is included in the 2007 ENERGY STAR criteria.

Table 11: ENERGY STAR Metrics for Dishwashers

	Dishwashers	
Energy Factor[1]	**Standard[2]**	**Compact[3]**
Energy Star	EF ≥ 0.65	EF ≥ 0.88
Federal	EF ≥ 0.46	EF ≥ 0.62

[1]**Energy Factor**: Expressed in cycles per kWh and is the reciprocal of the sum of the machine electrical energy, M, per cycle plus the water energy consumption per cycle, W.

$$EF = \frac{1}{M + W}$$

Dishwashers with a higher energy factor are more efficient.

[2]**Standard Dishwasher**: ≥ 8 place settings and six serving pieces.

[3]**Compact Dishwasher**: < 8place settings and six serving pieces.

Table 12: Company, Product and Patent Information for ENERGY STAR Database

	Enegy Star Appliance Classes				
	Clothes Washers	**Dehumidifiers**	**Dishwashers**	**Refrigerators**	**Room Air Conditioners**
Total # Companies with ES Certified Products	33	15	49	59	34
Total # ES Certified Products	341	198	734	1,727	762
Primary Patent Class	D32/1: Washing, Cleaning, or Drying Machine	D23/359: Environmental Heating and Cooling; Fluid Handling and Sanitary Equipment/Dehumidifier	D32/2: Washing, Cleaning, or Drying Machine: Dishwasher type	62/3.6: Refrigeration: Interior of enclosure cooled; e.g., refrigerator	62/262: Refrigeration: Window connected or mounted
Total # of Issued Patents	186	24	109	155	234
Additional Patent Classes	D32/5: Combined, e.g., washer and dryer	D23/314: Heating or Cooling	D32/8: Dryer or Extractor	165: Heat Exchange	
	D32/6: Laundry or dry leaning type		D32/22: Upright Type		
	D32/25: Element or Attachment		D32/26: Agitator		
	D32/26: Agitator		D32/27: Wringer		
	D32/27: Wringer		D32/29: Tub or Drum		
	D32/28 Control Panel therefor				
	D32/29: Tub or Drum				

Table 13: Portion of ENERGY STAR Database for Kenmore Dishwashers

Energy Star Database for Kenmore Dishwashers						
Model	**kWh/Year**	**Energy Factor (EF)**	**Federal Standard (EF)**	**Percent Better**	**Active**	**Active Date**
1349*K	363	0.59	0.46	28%	Yes	12/20/2005
1359*K	363	0.59	0.46	28%	Yes	12/20/2005
1367*K	357	0.61	0.46	33%	Yes	6/6/2006
1368*K	357	0.61	0.46	33%	Yes	6/6/2006
1369*K	363	0.59	0.46	28%	Yes	12/20/2005
1370*K	369	0.58	0.46	26%	Yes	6/6/2006
1371*K	357	0.61	0.46	33%	Yes	6/6/2006
1372*K	349	0.62	0.46	35%	Yes	6/6/2006
1373*K	349	0.62	0.46	35%	Yes	6/6/2006
1374*K	349	0.62	0.46	35%	Yes	6/6/2006
1375*K	357	0.61	0.46	33%	Yes	12/20/2005
1376*K	362	0.60	0.46	30%	Yes	12/20/2005
1377*K	362	0.60	0.46	30%	Yes	12/20/2005
1378*K	362	0.60	0.46	30%	Yes	12/20/2005
1379*K	362	0.60	0.46	30%	Yes	12/20/2005
1380*K	369	0.58	0.46	26%	Yes	6/6/2006
1381*K	357	0.61	0.46	33%	Yes	6/6/2006
1382*K	349	0.62	0.46	35%	Yes	6/6/2006
1383*K	349	0.62	0.46	35%	Yes	6/6/2006
1384*K	349	0.62	0.46	35%	Yes	6/6/2006
1385*K	357	0.61	0.46	33%	Yes	12/20/2005
1386*K	362	0.60	0.46	30%	Yes	12/20/2005
1387*K	362	0.60	0.46	30%	Yes	6/6/2006
14143	347	0.62	0.46	35%	Yes	4/5/2004
14144	347	0.62	0.46	35%	Yes	4/5/2004
14153	*328*	*0.65*	*0.46*	*41%*	*No*	*4/5/2004*
14154	*328*	*0.65*	*0.46*	*41%*	*No*	*6/7/2004*
14183	374	0.58	0.46	26%	Yes	6/8/2006
14184	374	0.58	0.46	26%	Yes	6/8/2006
14202	*328*	*0.65*	*0.46*	*41%*	*No*	*4/17/2003*
14209	*328*	*0.65*	*0.46*	*41%*	*No*	*4/17/2003*
14302	*347*	*0.62*	*0.46*	*35%*	*No*	*2/13/2003*
14303	347	0.62	0.46	35%	Yes	2/11/2005
14309	*347*	*0.62*	*0.46*	*35%*	*No*	*2/13/2003*
14432	370	0.58	0.46	26%	Yes	6/7/2004
14439	370	0.58	0.46	26%	Yes	6/7/2004
14538401	373	0.58	0.46	26%	Yes	2/28/2006
15142	347	0.62	0.46	35%	Yes	4/5/2004
15149	347	0.62	0.46	35%	Yes	4/5/2004
15152	*328*	*0.65*	*0.46*	*41%*	*No*	*4/5/2004*
15157	347	0.62	0.46	35%	Yes	2/11/2005
15158	*328*	*0.65*	*0.46*	*41%*	*No*	*6/20/2005*
15159	*328*	*0.65*	*0.46*	*41%*	*No*	*4/5/2004*
15162	*319*	*0.67*	*0.46*	*46%*	*No*	*4/5/2004*
15164	*319*	*0.67*	*0.46*	*46%*	*No*	*4/5/2004*
15169	*319*	*0.67*	*0.46*	*46%*	*No*	*4/5/2004*
15173	*347*	*0.62*	*0.46*	*35%*	*No*	*4/18/2005*
15182	374	0.58	0.46	26%	Yes	8/26/2005

9 References

1. Altshuller, G., *The Innovation Algorithm*. 1973, Worcester, MA: Technical Innovation Center Inc.

2. www.energystar.gov.

3. Dhillon, B.S., *Design for Reliability*, in *Environmentally Conscious Mechanical Design*, M. Kurtz, Editor. 2007, John Wiley & Sons: Hooboken, New Jersey. p. 161-184.

4. Dieter, G., *Engineering Design*. 3rd ed. 2000, New York: McGraw-Hill.

5. Fitzgerald, D., et al., *Beyond Tools: A Design for Environment Process.* Inetrnational Journal of Performability Engineering, 2005. **1**(2): p. 105-120.

6. Handfield, R., et al., *Integrating Environmental Concerns into the Design Process: The Gap Between Theory and Practice.* IEEE Transactions on Engineering Managment, 2001. **48**(2): p. 189-208.

7. Linton, J., *DEA: A Method for Ranking the Greeness of Design Decisions.* Journal of Mechanical Design, 2002. **124**: p. 145-150.

8. Okogbaa, O.G. and W. Otieno, *Design for Maintainability*, in *Envrionmentally Conscious Mechanical Design*, M. Kurtz, Editor. 2007, John Wiley & Sons: Hooboken, New Jersey. p. 185-248.

9. Sridhar, I., *Materials Selection for Green Design*, in *Environmentally Conscious Mechanical Design*, M. Kurtz, Editor. 2007, John Wiley & Sons Inc.: Hooboken, New Jersey. p. 319-350.

10. Astebro, T. and J. Michela, *Predictors of the Survival of Innovations.* Journal of Product Innovation Management, 2005. **22**.

11. Shah, J., N. Vargas-Hernandez, and S. Smith, *Metrics for Measuring Ideation Effectiveness.* Elsevier Science Ltd, 2002.

12. Bras, B., *Incorporating Environmental Issues in Product Design and Realization.* Industry and Environment, 1997. **20**(1-2).

13. Fussler, C. and P. james, *Driving Eco-Innovation: A Breakthrough Discipline for Innovation and Sustainability*. 1996, Washington DC: Pitman Publishing.

14. McDonough, W. and M. Braungart, *Cradle to Cradle: Remaking the Way We Make Things*. 2002, New York: North Point Press.

15. Fiksel, J., *Design for Environment: Creating Eco-efficient Products and Processes*. 1996, New York: McGraw-Hill.

16. Fitzgerald, D., *ENVRIZ: A Methodology for Generating Environmental Innovations*. 2006, University of Maryland, College Park.

17. Fitzgerald, D., et al., *Design for Environment (DfE): Strategies, Practices, Guidelines, Methods, and Tools*, in *Environmentally Conscious Mechanical Design*, M. Kutz, Editor. 2007, John Wiley & Sons Inc.: Hooboken, New Jersey.

18. *Eco-efficient Leadership for Improved Economic and Environmental Performance*. in *World Business Council for Sustainable Development*. 1995. Geneva.

19. Liu, C.-C. and J.L. Chen, *Development of Product Green Innovation Design Method.* IEEE, 2001.

20. Bohm, M., J. Vucovich, and R. Stone, *Capturing Creativity: Using a Design Repository to Drive Concept Innovation*, in *DETC*. 2005: Long Beach, California.

21. Hirtz, J., et al., *A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts.* Research in Engineering Design, 2005. **13**: p. 62-82.

22. http://function.basiceng.umr.edu/delabsite/repository.html.

23. Kurtoglu, T., et al., *Deriving a Component Basis for Computational Functional Synthesis*, in *International Conference on Engineering Design*. 2005, ICED: Melbourne.

24. Stone, R., *UMR Design Repository*. 2007.

25. Pahl, G. and W. Beitz. *Engineering Design: A Systematic Approach*. in *Design Council*. 1984. London.

26. Liu, C.-C. and J.L. Chen, *An Eco-Innovative Design Approach Incorporating the TRIZ Method without Contradiction Analysis.* The Journal of Sustainable Product Design, 2001. **1**(4): p. 263-272.

27. Chang, H.-T. and J.L. Chen, *Eco-Innovative Examples for 40 TRIZ Inventive Principles.* The TRIZ Journal, 2003.

28. Sandborn, P. and M. Vertal, *Analyzing Packaging Trade-Offs During System Design.* IEEE Design & Test of Computers, 1998.

29. Allen, D., et al. *Environmentally Benign Manufacturing: Trends in Europe, Japan and the USA*. in *DETC*. 2001. Pittsburg, PA.

30. http://en.wikipedia.org.

31. www.cultural-creatives.net.

32. Clarke, A. and J. Gershenson, *Life-Cycle Design*, in *Environmentally Conscious Mechanical Design*, M. Kurtz, Editor. 2007, John Wiley & Sons Inc: Hooboken, New Jersey. p. 67-126.

33. http://www.sei.cmu.edu.

34. Gupta, P., *Six Sigma Business Scorecard*. 2nd ed. 2007, New York: McGraw-Hill.

35. Constable, G. and B. Somerville, *A Century of Innovation*. 2003, Washington DC: Joseph Henry Press.

36. http://www.dmme.virginia.gov/De/figure7-8.jpg.

37. 1680, I.S., *IEEE Standard for Environmental Assessment of Personal Computer Products, Including Laptop Person Computers, Desktop Personal Computers, and Personal Computer Monitors*. 2006, IEEE: New York.

38. Ashley, S., *Designing for the Environment.* Mechanical Engineering, 1993. **115**(3): p. 53-55.

39. Crotti, A., et al., *Trends of Evolutions and Patent Analysis: An Application in the Household Appliances Field*, in *The Future of Product Development*. 2007. p. 145-154.

40. Jaafar, I.H., et al., *Product Design for Sustainablility: A New Assessment Methodology and Case Studies*, in *Environmentally Conscious Mechanical Design*, M. Kutz, Editor. 2007, John Wiley & Sons Inc: Hooboken, New Jersey.

41. Lindahl, M. *Designer's Utilization of DfE Methods*. in *Proceedings of the 1st International Workshop on "Sustainable Consumption"*. 2003. Tokyo, Japan.

42. Mauritz, D., *Buying Energy-Efficient Products*. 2005: US Department of Energy.

43. Middelkoop, T., D. Pepyne, and A. Deshmukh, *Analysis of Negotiation Protocols for Distributed Design*, in *Decision Making in Engineering Design*, K. Lewis, W. Chen, and L. Schmidt, Editors. 2006, Consortium for Distributed Decision Making.

44. Schmidt, L. and G. Dieter, *Engineering Design*. 2007, University of Maryland.

45. Serban, D., et al., *A TRIZ Approach to Design for Environment*, in *Product Engineering*. 2005. p. 89-100.

46. www.life-cycle.org.