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ON THE USE OF AXIOMATIC DESIGN FOR ECO-DESIGN

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ABSTRACT

Eco-design is of increasing import, especially since the decisions made in early design stages largely dictate not only the cost, but also the environmental effects, of a product. With the goal of providing guidance to engineers searching for methods to conduct eco-design, we consider the incorporation of ecological issues into the Axiomatic Design methodology. It is shown that there are natural ways to include eco-factors into every part of the design process using Axiomatic Design. Once we provide logical justification for the inclusion of eco-factors as functional requirements and design parameters, we proceed to demonstrate how Axiomatic Design can be used to analyze and design eco-friendly products. We conclude with a detailed design example of an eco-friendly flashlight.

Keywords: Sustainable product design, Eco-design, Axiomatic Design, Life cycle analysis

1 INTRODUCTION

To provide guidance to engineers seeking to develop more eco-friendly products, we investigate the use of Axiomatic Design in the eco-design context. We show that despite the fact that ecological issues are deeply coupled with product functions, there are several arguments for including both product functional requirements and ecological functional requirements. To incorporate life cycle analysis methods, which are similar to cost in that they are deeply coupled with product functions, we suggest an augmented design matrix that draws inspiration from the combination of cost engineering and Axiomatic Design. Finally, examples of the use of Axiomatic Design to analyze and design eco-friendly products are presented. It is our hope that the discussion will be of value to engineers seeking to use Axiomatic Design to create eco-friendly products and services.

1.1 MOTIVATION

Ecological issues are of growing import not only to protect our environment but because it is often good for business. As discussed in Brezet and Hemel [1997] and Graedel and Allenby [1995], customer awareness of the environment and the effect a product may have has increased.

There have been many efforts to restrict the ecological damage caused by products and services and to evaluate the ecological effect of a product. Numerous standards and regulations, such as the Restriction of Hazardous Substances (RoHS) directive of the European Union and the Waste Electrical and Electronic Equipment (WEEE) directive in the United Kingdom, have been introduced to protect the public from harmful contaminants. The Life Cycle Assessment (LCA) method was developed to calculate the environmental effect that a product will cause over its lifetime from cradle to grave (see, for example, Alting and Legarth [1995]). The ISO 14040:2006 standard details how LCA is to be conducted.

As evidenced by the issuing of ecologically related position statements on their public webpage, some companies have embraced the idea that ecological issues must be considered in product design and use existing eco-design methods. In addition to directives and assessment tools, checklists (e.g., Mok, *et al.* [2008]) and formal design methodologies such as QFDe, Green QFD (Zhang *et al.* [1999]), the Function Impact Matrix (Devanathan [2010]) and others (e.g., Park and Lee [2004]) have been employed.

As discussed by numerous authors including Ullman [1997], Dewulf and Deflou [2004], Fargnoli *et al.* [2005], Sousa and Wallace [2006], it is widely recognized that the decisions made in the early stages of a design contribute substantially, not only to the cost, but to ecological effects of the final product. Thus it is essential to consider ecological issues early in the design process. While methodologies such as Green QFD have been employed to address this need, there have been limited efforts to formally address environmental issues in the Axiomatic Design context.

1.2 RELATED AXIOMATIC DESIGN LITERATURE

There has been some effort to discuss the application of Axiomatic Design to eco-design. We review the most relevant work here.

In work that is most closely related to our efforts, Wallace and Suh [1993] focused on how information content, that is, Axiom 2, can be used to address the probability of meeting desired tolerance levels for environmentally related functional requirements. They also reviewed the status of a software tool that was under development to incorporate ecological design issues into the Axiomatic Design methodology. They provided some examples of ecologically related functional requirements, design parameters and design matrices relating them.

The quest to incorporate ecological issues into the Axiomatic Design methodology then lay dormant in the literature for over a decade. In Stiassnie and Shpitalni [2007], the use of Axiom 2 to conduct environmental effect assessment was considered; they added ecological issues into the design process for a manufacturing system that was initially considered in Suh [2001]. The evolution of the design of the Sihwa Dam in Korea was studied using Axiomatic Design in Ibragimova *et al.* [2009]. Functional requirements and design parameters (and the design matrix relating them) that specifically addressed ecological concerns were included. Finally, Thompson [2010] provided a detailed review of the growing use of ecological issues in the freshman design course at an engineering university in South Korea. Numerous issues related to eco-design, such as where such issues should be included in the design process, were considered.

Unlike the LCA procedure, which provides a clear categorization of ecological effects, there has been little effort to develop structured lists of ecological issues for use in the QFD and Axiomatic Design methodologies. While Wallace and Suh [1993] have taken some steps to develop ecological functional requirements (hereafter referred to as eFRs) and ecological design parameters (hereafter referred to as eDPs), more effort is required. Further, there is little justification or discussion that has been provided for which ecological issues (hereafter referred to as eco-factors) should be considered in the design process and where they should be addressed. Such considerations are non-trivial especially in light of the fact that, as stated in Tomiyama, Umeda and Wallace [1997], "[e]nvironmentally-conscious design requires the balance of a variety of deeply coupled issues".

There have been only a few efforts to discuss the concept of decoupling and how it can be applied to the analysis and design of ecologically friendly products, services and systems.

1.3 CONTRIBUTION AND ORGANIZATION

It is our aim to address the aforementioned needs. In particular, the contributions of this work are as follows. We

1. Develop a logical justification for the location of various eco-factors in the Axiomatic Design process (Section 2);
2. Collect an "exhaustive" list of eco-factors from the literature and organize them based on our classification for use in the design process (Section 3);
3. Augment the design matrix (DM) to include environmental assessment information so that there is a mechanism for the direct feedback of eco-analysis results into the design process (Section 4);
4. Provide several examples of how Axiom I well describes the decoupling achieved by existing eco-friendly designs (Section 5); and
5. Use Axiomatic Design for the detailed eco-friendly design of a flashlight (Section 6).

Concluding remarks are provided in Section 7. Note that some of the ideas discussed in detail here were briefly mentioned in the conference paper by Shin, Morrison and Suh [2010]. There, the focus was on developing a structure that can be used to create software to support an eco-friendly Axiomatic Design process.

We focus only on the customer, functional and physical domains. That is, we do not discuss process variables (PVs).

2 ECO-FACTORS IN THE DESIGN PROCESS

As discussed in Thompson [2010], the formal Axiomatic Design process begins with the collection or generation of the explicit and implicit desires of all stakeholders in the design process. These are termed customer needs (CNs). Since it is our intent to address ecological issues as well as basic product or service functions, here one must include environmental concerns or eco-factors. The CNs are typically non-specific, contradictory, biased, dependent and otherwise unstructured. For use in the design process, the designer must next structure and formalize the CNs into functional requirements (FRs), constraints (Cs), selection criteria (SC) and optimization criteria (OC). The CNs may also contain suggested design parameters (DPs) and process variables (PVs). Where should the various ecologically related CNs be placed in the design process? This is the question for which we aim to provide guidance in this section.

Note that the papers discussed in Section 1.2 above have all categorized their eco-factors into FRs, DPs, PVs Cs, SC or OC. Wallace and Suh [1993] provide the most general list of eco-factors and their corresponding location in the design process. However, they have not provided general thoughts or justification to guide the categorization. In fact, as mentioned in Thompson [2010], it is not uncommon for designers to incorrectly classify the eco-factors. However, it is important to note that, as Thompson [2010] stresses, the most successful eco-friendly projects will be those that include ecological issues in every part and phase of the design.

Hereafter, we use eFR if we specifically want to refer to ecologically oriented functional requirements. Similarly, we use eDP, eC, eSC and eOC.

2.1 ECO-FUNCTIONAL REQUIREMENTS

For proactive eco-design, it is essential that eco-factors be included in the functional requirements. By definition, FRs are goals that are required to be independent. If a need cannot be made or considered independent, it must be moved to another location in the design process such as a constraint, which has no such independence requirement. The difficulty with eco-factors is that they are generally considered to be coupled with the product functions. As such, they may be relegated to the status of constraint or selection/optimization criteria. There are two key concepts we use to distinguish eFRs.

2.1.1 ARGUABLY INDEPENDENT EFRS

First, if the eco-factor can be argued as independent, perhaps by appealing to the conceptual existence of a design for which there is no relationship between the proposed eFR and the product FRs, then the eco-factor can be considered as an eFR. We call such eFRS as *Type I eFRs*. As an example, suppose that a software company wants to

- FR1: Provide a video game experience, and
- FR2: Protect the environment.

Clearly there is no relationship between these two functions. However, one can more clearly see this by considering DPs

- DP1: Downloadable video game software, and
- DP2: Tree planting program.

Since the downloadable software consumes no materials (and nominally no energy that would not otherwise be consumed), it is independent of eco-factors. The tree planting program could be restricted to plant one tree per software sale and still maintain independence by using a constraint, or directly as a part of DP2 since DP1 is not related to software sales. In Thompson [2010], the eFR "Protect the environment" is used for the development of an eco-friendly tidal dam.

2.1.2 ADDITIONAL DPS ARE SPAWNED FROM EFRS

Second, if an additional design parameter is required beyond those needed to satisfy the product functions, then the ecological goal that the DP is striving to satisfy can be considered as an eFR. We call such FRs as *Type II eFRs*. This idea follows from Theorem 4 of Suh [2001] which states that in an ideal design the number of FRs and DPs are equal. While it is possible to have extra DPs in a good design, termed redundant design, such redundancy will not occur for DPs that exist strictly to address ecological goals rather than basic product goals.

As an example, consider the design of chair legs to support 100 kg under the nominal gravitational force of the earth. Three concepts for the chair legs, including their FRs and DPs are depicted in Figure 1. The top design is simply a cylinder that fulfils all product FRs. The second design adds an additional cylindrical hole through the z-axis of the original cylinder; this is an additional DP. The purpose of this DP is to allow the leg to consume the least physics based volume of material while still supporting the weight. This eDP is directional so that, in the bottom design, the idea can be extended to the vertical plane via the inclusion of additional eDPs. The eFR that we associate with these additional eDPs is to "Consume the physics based minimal amount of material" with a focus on a particular axis.

Note that these eDPs are not simply a change in the density of the original design. Rather, there is a structural difference and a DP associated with it that enables one to strive for the physics based minimal amount of material.

Note also that we motivated this eFR based on the recognition of an eDP. This is the reverse of the zig-zag approach that one should use for design. However, it was merely used to justify the existence of the eFR. Now that we have recognized the eFR, it can be associated as a child function of any product FR that uses a DP consuming material. This eFR should prompt the designer to seek a new DP that allows improved eco-performance while retaining the original product functions.

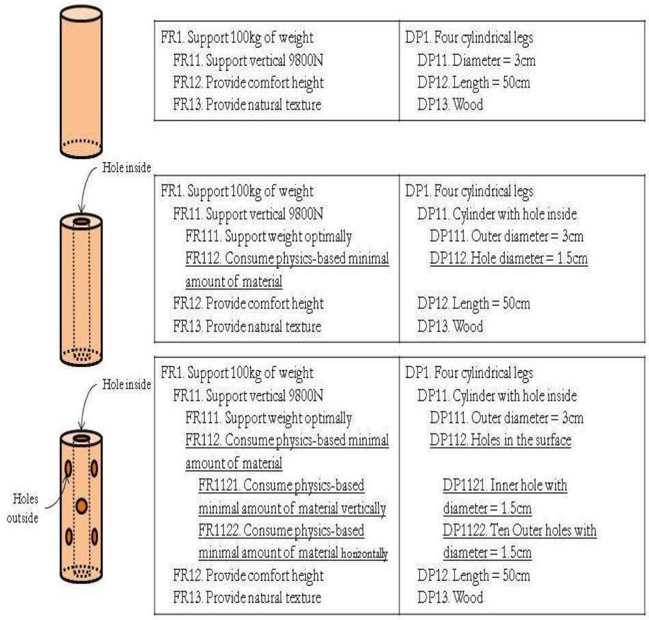

Figure 1. Additional eDPs are present.

2.1.3 COMMENTS ON EFRS

Type I eFRs are outside of the product itself and strictly exist to address the concerns of stakeholders for the environment. While a particular design may couple the functions, we consider that "protect the environment" is an independent FR. Type II eFRs are closely related to the product. Such eFRs may provide motivation for *structural choices* that exist solely to achieve a minimal amount of material and thus require their own DP. This is to be contrasted from the typical admonition to minimize the amount of material used – the solution there is simply to *optimize the quantity without new DPs* for structural changes. In this Type II eFR category we will place "return material to source". This eFR can be solved by adding DPs that enable the product to be more readily recyclable. Because Type II eFRs require additional DPs associated with a higher level product FR (see the chair leg example), we will call them children of product FRs, or CoPFRs.

It may be possible that the customer oriented FRs cannot be thought of as independent of the environment, perhaps because their very existence is antithetical to green needs. However, in such instances, the designers should rethink their product goals. For product functions that appear tightly coupled with ecological issues by physical laws, one should consider that physical laws are often imposed once a design choice is selected. If a different design choice is made, there may be no relationship between the environmental goals and the product ones.

2.2 ECO-DESIGN PARAMETERS

An eDP is a concept or part whose purpose is to provide an eFR. It must truly be separate from the DPs that fulfil other types of FRs and cannot be contained in them. For example, "minimize the variety of materials used" might be considered as an eDP as it is a method to achieve an ecological goal. (Wallace and Suh [1993] use it as an eDP.) However, we do not consider it to be an eDP since the material choices must be made to satisfy the product FRs. A restriction on the number of different materials used is either a constraint, selection/optimization criteria or simply a strategy that can be used to improve the LCA outcome of the product. The eDP must not merely try to ease some environmental requirement but be essential for performing it.

For example, while single material construction affords an ease of recycling, all materials must already exist as product DPs. They are simply chosen to be of the same type to improve the recyclability of the product. On the other hand, we do consider additional parts, such as a thumb tab that allows easy disassembly, to be viable eDPs. They exist solely to satisfy an eFR (in this case "return material to source").

Consider another example. If instead of using steel for a part, we instead use wood to improve the environmental assessment of the product, this choice does not represent a new DP. This is the optimization of existing DPs.

2.3 ECO-CONSTRAINTS AND SELECTION CRITERIA

Considerations such as LCA values, carbon footprint and the like are dependent upon every design choice made and closely depend upon the product functions. They are similar to cost. As such we relegate them to the status of selection criteria, optimization criteria or constraints. RoHS and WEEE directives are constraints; they limit the materials that can be used in a design.

As such, achieving a "minimal carbon footprint" or "minimal LCA value" depends deeply on the DPs selected to provide the non-eFRs. The act of minimization belongs more appropriately in the realm of selection/optimization criteria. Such eco-factors are similar to cost and it is more appropriate to include them as an eC, eSC or eOC. Of course, there may be exceptions.

3 CLASSIFICATION OF ECO-FACTORS

Unstructured environmental factors can be difficult to include in a formal design methodology. A number of researchers have developed structured eco-factors, but these are not appropriate for the Axiomatic Design framework. Though Wallace and Suh [1993] appear to have developed eFRs and eDPs, the details of the work are unpublished and not justified. Also, our classification is different in that we only allow eDPs if there is a new part or design concept associated with the eFR.

We collected hundreds of unstructured eco-factors from the literature and from company websites. The eco-factors included but were not limited to OECD environmental key indicators ([2004]), environmental benchmarking parameters (Yim and Lee [2002], and Park and Lee [2004]), environmentally friendly manufacturing checklists (Mok *et al.* [2008] and Mok and Cho [2001]), ecodesign strategies for electronics products (Park and Lee [2004]), LCA categories (ISO [2002], ISO [2006] and ISO [2006]) and strategies for developing eco-friendly products (e.g., design for recycling, green purchasing, fuel efficiency, upgradability, ease of assembly, etc.).

These collected eco-factors were considered as eCNs. First, we separated the eCNs into goals and methods. Goals were classified as eFR candidates and methods and solutions were classified as DP candidates. We grouped these candidates into the categories: material, energy and waste. Candidate eFRs and eDPs were eliminated if they did not logically fit into the eFR and eDP categories as described in Section 2. eCNs failing to meet the eFR or eDP criteria were relegated to the status of eCs, eSC or eOC. Finally, we combined and reworked the eCNs in an effort to ensure that they fit with the requirements of FRs and DPs. That is, among others, FRs should start with a verb, be specific, independent and solution neutral. Similar considerations were taken for the DPs. The eFR and eDP lists are shown in Figures 2 and 3. The zero-th level FR "Protect the Environment" is not shown.

FR1. Preserve material	DP1. Program for material resource replenishment
FR11. Collect used material	DP11A. Collection program for material from used product (same with designed product)
	S11A1. Design for disassemble ability
	S11A2. Material homogeneity
	DP11B. Collect program for material from used product (different products)
	DP11B1A. Incentive for returning products
	DP11B1B. Contract with other companies
	DP11C. Collect program for scraped material
	DP11C1A. Internal company system to Collect scraped material
	DP11C1B. Contract with other companies
FR12. Transport used material	DP12. Transport system for used material
	S121. High stack ability
	S122. Simple structure
	S123. Low weight
	S124. Low volume
FR13. Re-process used material	DP13. Re-processing for used material
	S131. High durability
	S132. Design for disassemble ability
	S133. Part standardization
	S134. Design for easy test
	S135. Design for easy cleaning
FR2. Preserve energy generating material	DP2. Energy resources replenishment
	S2A. Infinite energy source
	S2B. Use leftover energy to different purpose
FR3. Preserve integrity of the environment	DP3. Program for preserve integrity of the environment
	DP3A. Plant tree
	DP3B. Purification system for environment

Figure 2. Type I eFRs and possible eDPs.

Figure 2 provides an organized list of Type I eFRs and possible eDPs to achieve them. Additional items marked as, for example, S121 or S123 are strategies that may be used to help select the next level eDPs or as optimization criteria to improve the ecological outcome targeted by the eFRs and eDPs. For example, "S121 High stackability" may be achieved by the inclusion of structural elements (new DPs) that ensure the stacking of products after disposal. On the other hand, "S123 Low weight" is a selection criterion or an optimization criterion that can be employed. Figure 3 similarly provides Type II eFRs and possible eDPs.

Note that the development of such a structured list is merely an attempt to collect and organize existing eco-factors. There are no doubt many other such eco-factors that could be included here. The creation of pre-prepared eFRs and eDPs is an ongoing and unending task as new ideas will arise in the literature.

4 AUGMENTED DESIGN MATRIX

To facilitate the inclusion of cost in the Axiomatic Design process, Lee and Jeziorek [2004] proposed that a mapping be created between the physical domain (DPs) and the costing unit domain (or simply cost domain). Costing units (CUs) are parts and systems to which a cost can be associated. Note that DPs may not be costing units since they can be angles or dimensions as opposed to a complete part. Here, we propose that a similar mapping be employed between the DPs and any selection criteria. As in Lee and Jeziorek [2004], we will assume that there is a mapping between the DPs and SC units. As we have a particular interest in ecological assessment, LCA values are suggested for inclusion in addition to cost.

FR1. Preserve material	DP1. Structure to preserve material
FR11. Consume physics-based minimal amount of material	DP11. Structure to achieve physics based minimal amount of material
	S111. Structural change
	S112. Physical integration
	S113. Composite material
FR12. Provide easy condition to material resource replenishment	DP12. Structure enabling easy replenishment of material resource
	S121. Design for disassembly
	S122. Material homogeneity
	S123. Simple structure
	S124. High durability
FR2. Preserve energy generating material	DP2. Structure to preserve energy generating material
FR21. Consume physics-based minimal amount of energy	DP21. Structure to minimize additional energy consumption
	S211. Increase energy efficiency
	S212. Low weight
	S213. System for manual energy generation
	S214. Use natural power (gravity, air...)
FR22. Replenish energy resource	DP22. Structure to replenish energy resource
	S221. Infinite energy source
	S222. Self energy generation system
	S223. Use of leftover energy for a different purpose
FR3. Preserve integrity of the environment	DP3. Structure to preserve integrity of the environment
FR31. Minimize harmful waste	DP31. Structure to minimize harmful waste
	S311. Use less material
	S312. Use natural material
	S313. Capture harmful waste
FR32. Convert potentially harmful waste into harmless material	DP32. System/process to convert waste into harmless material
	S321. Recycling
	S322. Neutralization
	S323. Purification

Figure 3. Type II eFRs and possible eDPs.

To clearly display the selection criteria values such as total cost and total LCA score, as well as highlight how much each costing unit or part contributes to the overall value, we employ an augmented design matrix (DM). Beneath the final row of the traditional DM, we append one row for each selection criteria to be evaluated. For each such SC, we require that:

1) The costing units or SC units to which we associate SC values exist as a subset of the DPs; and
2) The total score for the SC (e.g., total cost) can be obtained as the sum of the highest level SC unit scores.

Figure 4 depicts such an augmented design matrix. There, an additional row is added for each SC to be included.

Note that since the SCs do not have associated DPs, the augmented design matrix is not square. The values in the augmented DM in the new rows are the cost or LCA value associated with those DPs that are included as an SC unit. Those DPs which do not have an associated SC unit are left blank. Summing the values for the highest level DPs (SC units) gives the total cost or LCA value for the design. Values may be assigned to lower level DPs (SC units) with the understanding that such values sum to give the score for their parent DP.

It is important to note that LCA values are not available until the product has been completely designed at the detailed level. However, there are other approximate methods that can predict LCA values for a product at any stage of the design process (more or less well, however). It is these methods that must be employed in the early stages of the design to populate the augmented design matrix.

An example of the augmented design matrix will be given in our design example of Section 6.

5 ECO-DESIGN EXAMPLES

In this section, we discuss via example how Axiomatic Design can well describe eco-friendly products. As mentioned in the introduction, others have used Axiomatic Design for eco-design. Here we study products that have not yet been analyzed, use our approach and develop a new idea for staple(r) design. That is, the decoupling demanded by Axiom I serves to naturally explain why a new design is more eco-friendly than the previous one. The first example is from a known system.

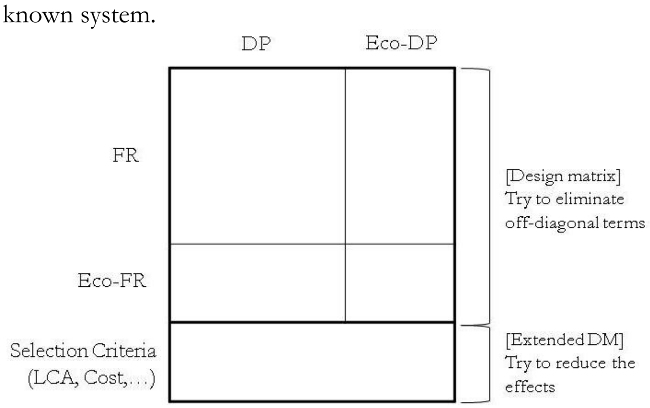

Figure 4. Augmented design matrix structure.

Example 1: Laundry and toilet system. Consider the objectives of washing clothes, expelling waste from a toilet and protecting the environment. The FRs and DPs for such a system are shown in Figure 5. The left portion of the figure provides the FRs and DPs for a system consisting of a separated washer and toilet. There, separate water sources are used for both the washer and the toilet. We consider that each influences our ability to protect the environment. The rightmost list of FRs and DPs is for the system depicted at the far right of the figure. In that system, the water from the washer is stored in "DP3. Water storage tank". By storing the water from the washer, no (or certainly significantly less) additional water is required from the tap to operate the toilet. As such, the coupling between DP2 and FR3 has been eliminated (or greatly reduced).

The next example was developed using the tools and structure proposed in this paper.

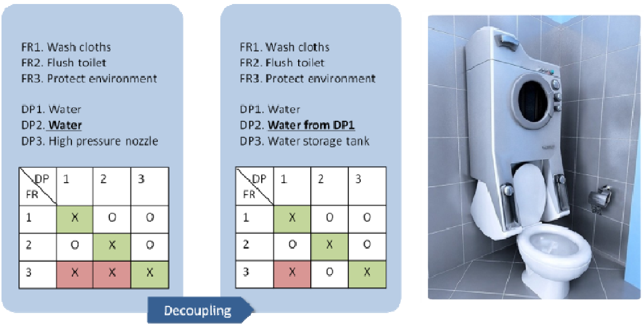

Figure 5. Design of a laundry and toilet system.

Example 2: Design of a stapler. According to Devanathan *et al.* [2010], staple consumption contributes the greatest to total stapler life cycle carbon footprint. We thus consider the redesign of a typical staple(r). First note that, the reason why a staple pierces the paper at two distant points is that these two points prevent adjacent sheets of paper from rotating relative to each other. In current staple(r) designs, the two points of the staple are connected. However, if the two staple points are no longer connected they will still provide the same protection from rotation between sheets of paper but it may be possible to use less material. Figure 6 provides a subset of the FRs and DPs for an existing staple structure and a new design. By recognizing that there is coupling between FR41 and DP121 that is not necessary, we obtain a new design for the staple(r). In the new design, two independent and smaller spikes of metal are used to pierce the paper at any distance from one another that is desired. The decoupling allows for the middle part of staple to be removed. This new concept may allow reduced material consumption and arose from the desire to remove coupling between the eFR and the product FRs.

6 DETAILED ECO-DESIGN EXAMPLE

In this section, we consider the detailed design of an emergency flashlight concept. Unlike the stapler of Example 2, where a decoupling opportunity was identified, our new flashlight design does not so much decouple functions as optimize the ecological performance. However, some couplings were removed or reduced. We use the eFRs and augmented design matrix described above.

Ecological issues were considered in all parts of the design process as well as in every part of the product. First, the CNs of emergency flashlights were obtained through surveys and website forums. Benchmarking was conducted with eight different types of emergency flashlights found in the market; the advantages of each product were identified, compared and later used as key features of the design.

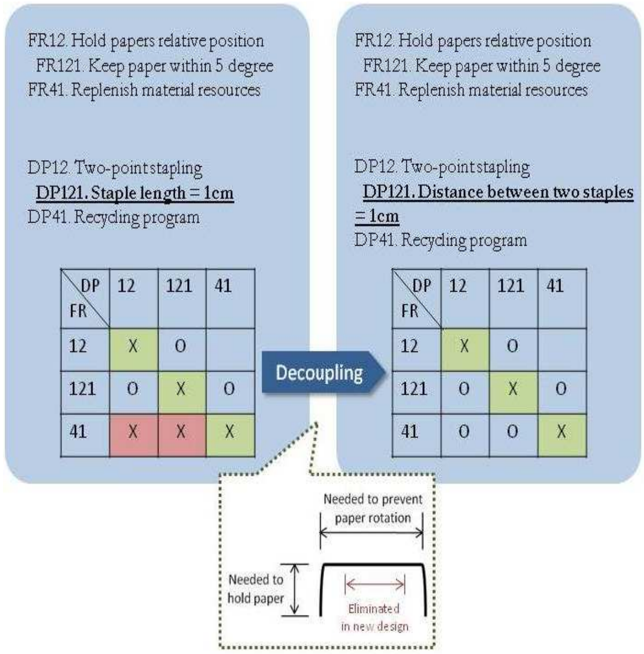

Figure 6. Decoupling example for a staple(r).

Concept ideation incorporated the results from the benchmarking and the selected FRs. The FRs are depicted in Figure 7. Starting from existing designs, two different strategies were used to improve the ecological performance of the flashlight design: replace the battery with a more eco-friendly component and minimize the size of the flashlight.

Figure 8 shows the DPs for a benchmark emergency flashlight. The augmented design matrix representing the mapping between FRs and DPs is presented in Figure 9. Since we do not normally have exact LCA values at this stage of the design the following approach is used to estimate the LCA values. First, a value is specified to represent the magnitude of the relationship between the DPs and eco-FRs. Values are selected from a scale of 1 to 5; a high value means that the coupling between that FR and DP has a high effect on the environment and a low value indicates a weak effect. These values are then normalized by row so that they sum to 1.

LCA values for three categories of ecological effect (termed EC1, EC2 and EC3) were acquired from a standard flashlight; see the LCA value column. These effect values are then multiplied by the score in the augmented design matrix and summed for each DP to obtain an estimate of the total ecological effect for each DP. The row entitled "DP's effect value" represents the official row of the augmented design matrix. (The preceding rows labeled EC1, EC2 and EC3 are simply used to demonstrate the approach used here to approximate the LCA values).

In Figure 9, the total effect of DP12, DP14, DP23, and DP33 is the highest. The total effect of DP12 can be calculated as (1x500) + (1x50.13) =550.13. Therefore improving the light source, the rechargeable battery, plastic material and size of flashlight will reduce the LCA value.

FR1. Supplies light
- FR11. Supplies light in targeted area
- FR12. Supplies 45 lumens, 2 watts
- FR13. Supply energy for light

FR2. Enables emergency operation
- FR21. Absorbs energy from the environment
- FR22. Absorbs energy from user
- FR23. Resists impacts

FR3. Simple to use
- FR31. Requires little effort to absorb energy from user
- FR32. Enable user to operate mechanism in dark
- FR33. Portable

FR4. Protects the environment

Figure 7. FRs for an eco-flashlight.

DP1. Lighting mechanism
- DP11. Magnifying lens and reflector
- DP12. 3 LED light bulbs
- DP13. Rechargable battery

DP2. Emergency functions
- DP21. Solar panel
- DP22. Dynamo
- DP23. Plastic casing

DP3. Ergonomic structure
- DP31. Pull string operating cog wheels
- DP32. Glow in the dark operation buttons
- DP33. Size that fits in hand

DP4. Program to protect the environment

Figure 8. DPs for an eco-flashlight.

6.1 DECOUPLING

We next strive to eliminate couplings and produce a new design. A new concept whose DPs are given in Figure 10 and whose augmented design matrix is depicted in Figure 11 includes the following features. Note that for the EC1, …, DP's effect value rows, we have normalized using the sum of values from the benchmark design, since the new design has smaller values.

- Rechargeable battery: Chemicals used in the battery can be harmful after disposal. This coupling effect is eliminated by replacing the battery with the ultracapacitor. The ultracapacitor has no chemical reactions which eliminates the environmental impact. In this new design, additional material for casing can be reduced since the size of the energy storage is also reduced.
- Plastic material for casing: The thickness of the benchmarked flashlight ranged from 1.6mm to 5mm. By choosing to use 1.6 mm thickness of material for the casing of the flashlight, the environmental effect is reduced and durability of the product is still ensured.
- Small enough to grip by hand: Since the new concept uses an ultracapacitor, to guarantee maximum energy stored in less time, the number of turns of the dynamo should be increased but still use a minimum amount of space. This can be done when the size of the cog wheels is reduced to 27 teeth per cog wheel and the number of cog wheels is increased. Reducing size of cog wheels and replacing energy storage component reduces the burden of size of product to the environment.

Even though the light source has the greatest effect, no changes were made; it already emits sufficient lumens using a minimum amount of energy.

	LCA value	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP3	DP31	DP32	DP33	DP4
FR1		X				0	0	0	0	0	0	0	0	0
FR11			X	0	0	0	0	0	0	0	0	0	0	0
FR12			0	X	0	0	0	0	0	0	0	0	0	0
FR13			0	0	X	0	0	0	0	0	0	0	0	0
FR2		0	0	0	0	X				0	0	0	0	0
FR21		0	0	0	0		X	0	0	0	0	0	0	0
FR22		0	0	0	0		0	X	0	0	0	0	0	0
FR23		0	0	0	0		0	0	X	0	0	0	0	0
FR3		0	0	0	0	0	0	0	0	X				0
FR31		0	0	0	0	0	0	0	0		X	0	0	0
FR32		0	0	0	0	0	0	0	0		0	X	0	0
FR33		0	0	0	0	0	0	0	0		0	0	X	0
FR4		X	0	X	X	X	0	0	0	X	0	0	0	X
EC1	8.97		0.04	0	0.19		0.11	0.11	0.19		0.11	0.07	0.19	0
EC2	500		0.07	0	0.21		0.10	0.10	0.17		0.10	0.07	0.17	0
EC3	50.13		0.10	0	0.23		0.10	0.10	0.16		0.10	0.06	0.16	0
DP's effect value		156.10	39.67	0.00	116.43	211.10	57.57	57.57	95.95	191.91	57.57	38.38	95.95	0

Figure9. Augmented design matrix for basic flashlight.

DP1. Lighting mechanism
- DP11. Magnifying lens and reflector
- DP12. 3 LED light bulbs
- DP13. Ultracapacitor

DP2. Emergency functions
- DP21. Solar panel: Thin-film crystalline silicon (30x30 mm)
- DP22. Dynamo: Cylindrical (15x25 mm)
- DP23. Plastic casing of 1.6 mm thickness

DP3. Ergonomic structure
- DP31. Pull string operating 8 cog wheels (4x15 mm and 4x10 mm diameter)
- DP32. Glow in the dark operation buttons
- DP33. Size that fits in hand (28.12x24x77.41 mm)

DP4. Program to protect the environment

Figure 10. DPs of the eco-flashlight.

The final design of the product is depicted in Figure 12 and uses an ultracapacitor as the main component for energy storage. The size and shape of the product's casing was chosen to minimize the amount of material required. Figure 12 shows the top and side views.

	LCA value	DP1	DP11	DP12	DP13	DP2	DP21	DP22	DP23	DP3	DP31	DP32	DP33	DP4
FR1		X				0	0	0	0	0	0	0	0	0
FR11			X	0	0	0	0	0	0	0	0	0	0	0
FR12			0	X	0	0	0	0	0	0	0	0	0	0
FR13			0	0	X	0	0	0	0	0	0	0	0	0
FR2		0	0	0	0	X				0	0	0	0	0
FR21		0	0	0	0		X	0	0	0	0	0	0	0
FR22		0	0	0	0		0	X	0	0	0	0	0	0
FR23		0	0	0	0		0	0	X	0	0	0	0	0
FR3		0	0	0	0	0	0	0	0	X				0
FR31		0	0	0	0	0	0	0	0		X	0	0	0
FR32		0	0	0	0	0	0	0	0		0	X	0	0
FR33		0	0	0	0	0	0	0	0		0	0	X	0
FR4		X	0	0	X	X	0	0	0	X	0	0	0	X
FR41	10.4		0.04	0	0.11		0.11	0.11	0.07		0.07	0.07	0.04	0
FR42	500		0.07	0	0.10		0.10	0.10	0.07		0.07	0.07	0.03	0
FR43	56.76		0.10	0	0.10		0.10	0.10	0.06		0.06	0.06	0.03	0
DP's effect value		98.73	40.36	0.00	58.37	155.66	58.37	58.37	38.92	97.29	38.92	38.92	19.46	0.00

Figure 11. Augmented design matrix for eco-flashlight.

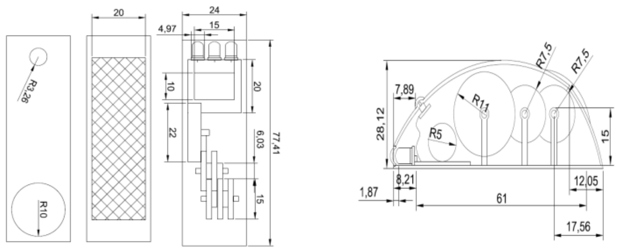

Figure 12. Component designs for eco-flashlight.

6.2 ANALYSIS

The benchmarked design was a BENEX flashlight that used a pull string dynamo and solar panel. The size of our benchmarked design is 17x50x130mm and the dynamo turned 182.25 times per pull of the string. Our new design is 28.12x24x77.41mm and produces 478.3 turns in one pull. Our new design has the same features, but it is more eco-friendly.

When choosing the best material for the flashlight, the lowest result of weight for the same amount of material multiplied by the amount of CO_2 emission of that material was used. In the benchmark products, plastic and aluminium were used. For aluminium the CO_2 total was 30.988 (15.81x1.96) and for plastic 26.641 (8.97x2.97). The plastic is best for this product.

The cost for a 500 mAh ultra capacitor is 2,683 KRW (see Mouser [16]). The cost for a 500 mAh li-ion battery is 638.8 KRW (see Mouser [17]). This is often the case when eco-friendly solutions are implemented since they include more advanced technologies. The cost will reduce when demand increases with growing awareness of more eco-friendly products.

7 CONCLUDING REMARKS

As the decisions made early in the design process dictate the majority of the product cost and ecological effect, it is essential to include eco-factors early. By demonstrating that eco-factors can be naturally included in the Axiomatic Design process in numerous locations, it is possible to employ the power of Axiomatic Design to influence early design decisions. In addition to providing justification for the locations of various eco-factors in the design process, we include LCA values (or other eco-assessment tools) as a selection criterion and augment the design matrix so that LCA results may be naturally included in the Axiomatic Design process. We demonstrated via example that ecologically friendly products can be analyzed and designed by this approach. Finally, we used Axiomatic Design and the ideas presented here for the design of an eco-friendly flashlight. It is our hope that the discussion presented here will serve as an aid to engineers seeking to develop more eco-friendly products and services.

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